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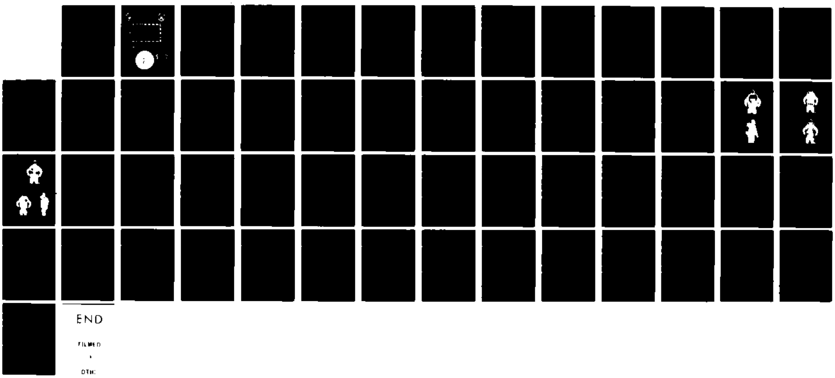

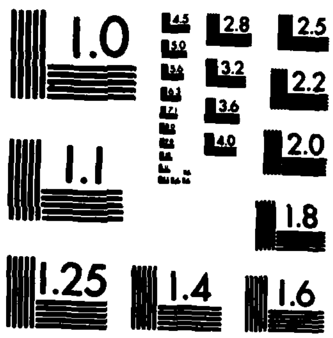

MICROCOPY RESOLUTION TEST CHART
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Navy Experimental Diving Unit

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UNMANNED EVALUATION OF SIX CLOSED-CIRCUIT OXYGEN REBREATHERS

JAMES R. MIDDLETON

JULY 1982

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UBA	breathing work	DRAEGER LAR V
oxygen	canister duration	FENZY PO.68
closed-circuit	AGA OXYDIVE	U.S. NAVY EMERSON
breathing resistance	REXNORD MOD BIOPAK 24D	SUBMARINE PRODUCTS OXYMAX 3

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Six closed-circuit (C/C) pure oxygen rebreathers were evaluated in the unmanned mode by the Navy Experimental Diving Unit in accordance with Naval Sea Systems Command Task Number 81-16. The purpose of the task was to provide performance data on existing rebreathers to aid in the selection of a new C/C pure oxygen underwater breathing apparatus (UBA) to replace the current U.S. Navy C/C SCUBA (EMERSON).

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BLOCK 20 CONTINUED:

Breathing resistance/breathing work studies were conducted using a hyperbaric breathing simulator at depths up to 40 feet-of-seawater (FSW) at simulated work rates ranging from light to extreme. Carbon dioxide (CO_2) absorbent canister duration tests were also conducted at 25 FSW in water temperatures ranging from 29 to 90°F.

Results of unmanned performance testing revealed the AGA OXYDIVE and DRAEGER LAR V C/C UBA's to have breathing resistance/breathing work and CO_2 absorbent canister durations superior to all other UBA's evaluated. One exception to this finding was that the Navy 'EMERSON' exhibited canister durations slightly superior to those obtained with the AGA and DRAEGER units.

Glossary

BPM	breaths per minute
C/C	closed-circuit
Canister Breakthrough	point at which CO_2 concentration in the inhaled gas reached 0.50 percent surface equivalent
°C	temperature degrees Centigrade
cmH_2O	centimeters of water pressure
CO_2	carbon dioxide gas
EDF	Experimental Diving Facility Hyperbaric Chamber Complex
°F	temperature degrees Fahrenheit
FFM	full-face mask
FSW	feet-of-seawater
HP	high pressure
HP SODASORB	high-performance SODASORB
kg·m/l	kilogram-meters per liter (respiratory work)
ltv	the liter-tidal volume of air breathed in and out of the lungs during normal respiration
lpm	liters per minute (flow rate)
MOD	modified
NAVSEA	Naval Sea Systems Command
NEDU	Navy Experimental Diving Unit
O/C	open-circuit
O_2	oxygen gas
ΔP	pressure differential (cmH_2O)
psid	pounds per square inch differential
psig	pounds per square inch gauge

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Glossary (continued)

RMV	respiratory-minute-volume in liters-per-minute
SCUBA	self-contained underwater breathing apparatus
SEV	surface equivalent value
SI	System International (units of measure)
TEMP	temperature
Texp	exhaled gas temperature
Tin	inspired gas temperature
UBA	underwater breathing apparatus
U/W	underwater

SI Unit Conversion Table

To Convert From	To	Multiply By
kg m/ℓ	joule per liter (J/L)	9.807
psi	kilopascal (kPa)	6.895
°C	kelvin (K)	°K = °C + 273.15
°F	kelvin (K)	°K = (°F + 459.67)/1.8
FSW	meters of seawater (MSW)	0.305
FSW	kilopascal (kPa)	3.065

Abstract

Six closed-circuit (C/C) pure oxygen rebreathers were evaluated in the unmanned mode by the Navy Experimental Diving Unit in accordance with Naval Sea Systems Command Task Number 81-16. The purpose of the task was to provide performance data on existing rebreathers to aid in the selection of a new C/C pure oxygen underwater breathing apparatus (UBA) to replace the current U.S. Navy C/C SCUBA (EMERSON).

Breathing resistance/breathing work studies were conducted using a hyperbaric breathing simulator at depths up to 40 feet-of-seawater (FSW) at simulated work rates ranging from light to extreme. Carbon dioxide (CO_2) absorbent canister duration tests were also conducted at 25 FSW in water temperatures ranging from 29 to 90°F.

Results of unmanned performance testing revealed the AGA OXYDIVE and DRAEGER LAR V C/C UBA's to have breathing resistance/breathing work and CO_2 absorbent canister durations superior to all other UBA's evaluated. One exception to this finding was that the Navy 'EMERSON' exhibited canister durations slightly superior to those obtained with the AGA and DRAEGER units.

I. INTRODUCTION

During October through December of 1981, NEDU tested six C/C pure O_2 rebreathers in accordance with NAVSEA Task Number 81-16. The purpose of unmanned testing was to evaluate performance to aid in the selection of a new O_2 UBA to replace the current U.S. Navy C/C O_2 SCUBA (EMERSON). Four of the UBA's were of foreign manufacture and two were produced in the United States. (APPENDIX A contains a list of manufacturer addresses and models tested.)

Unmanned testing was conducted in the NEDU EDF. The UBA's were evaluated with respect to breathing work and breathing resistance at simulated diver work rates ranging from light to extreme. In addition, each rebreather was tested to determine the duration of its (CO_2) absorbent canister at a variety of water temperatures ranging from 29°F to 90°F at 25 FSW.

NOTE: All six UBAs were tested with the flow pattern through the rebreather as follows: inhaling from the right hand hose and exhaling into the left hand hose.

II. FUNCTIONAL DESCRIPTION

The functional description of a C/C O_2 rebreather is illustrated in Figure 1. While each model differs in size, shape, internal layout and specific design parameters, the basic gas flow path, major components and functional design are similar. The O_2 add system is the main area of functional difference in C/C O_2 rebreather design. The AGA OXYDIVE, BIOPAK 240, DRAEGER LAR V, and FENZY PO 68 all have their O_2 demand valve located in the breathing bag or counterlung. The SUBMARINE PRODUCTS OXYMAX 3 has its O_2 demand valve located in the mouthpiece similar to a conventional SCUBA regulator. This allows the diver to shut off the C/C loop and operate in a completely O/C mode for emergency ascents in the event of a flooded CO_2 absorbent canister. In the O/C mode, the diver breathes directly off his O_2 bottle. While the duration of the gas supply in this mode is limited due to the small O_2 cylinders inherent in C/C UBA design, it does offer the diver an alternative breathing source in an emergency situation. The U.S. Navy EMERSON does not add O_2 via a demand valve. Oxygen is added to the breathing bags by a manually adjustable continuous flow metering valve. The valve, located in a block assembly on the right breathing bag, is set to the rate at which the diver uses oxygen.

A description of the basic operation of a C/C rebreather is as follows:

From the O_2 cylinder (1), HP O_2 passes through the cylinder on/off valve (2) to the pressure reducing regulator (3) where the HP gas is reduced to an over-bottom pressure setting, then piped to the demand valve (4). The demand valve, secured to the equipment case housing and fitted to the breathing bag (5), functions each time the bag is emptied on inhalation. On inhalation, the inhalation check valve (6) opens and the diver receives gas from the breathing bag. If not enough gas is available, the demand valve

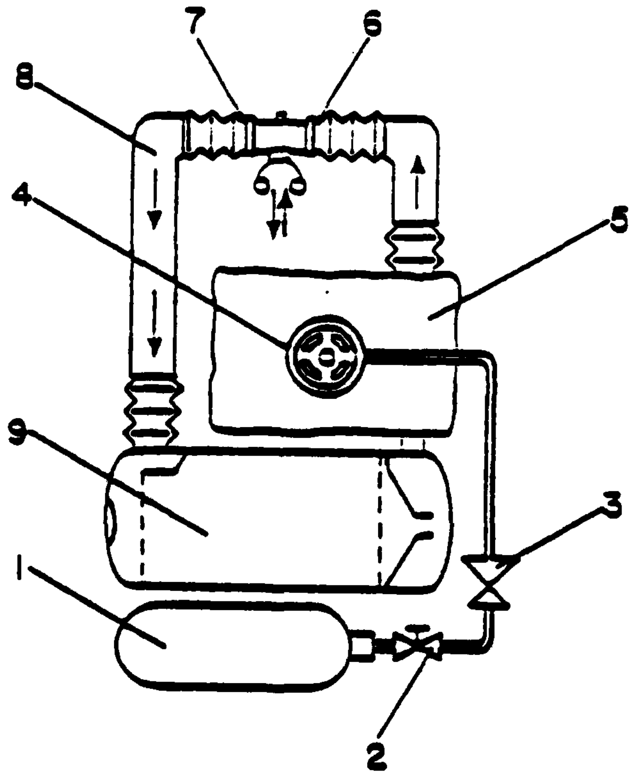


Figure 1. Functional Schematic

actuates, adding more O_2 to the system. As the diver exhales, the exhalation check valve (7) opens, the inhalation check valve closes and the exhaled gas flows through the exhalation hose (8) to the CO_2 scrubber (9); it is then drawn through the CO_2 scrubber (9) with the next inhalation. During descent, or to purge the unit, the diver merely depresses the demand bypass valve to add gas.

III. EQUIPMENT SPECIFICATIONS AND PHOTOS

APPENDIX B contains a complete list of manufacturer specifications on each UBA tested. In addition, photos of each UBA, as they appear when worn by the diver, are included (Figures 3 through 8).

IV. TEST PROCEDURE

A. Test plan

Figure 2 illustrates the test equipment set-up. APPENDIX C provides the complete test plan and the test equipment illustrated in Figure 2 is listed in APPENDIX D. A breathing simulator and hyperbaric chamber simulated diver inhalation and exhalation at various depths and diver work rates. The wet box in which the UBAs were submerged simulated the wide range of water temperatures in which the UBAs might be used. A total of five RMVs were tested at all normal operating depths to simulate light through extreme diver work rates. Breathing resistance was measured using a pressure transducer located in the oral cavity of the mouthpiece or the oral-nasal cavity of the FFM (OXYMAX 3 only). In addition, breathing resistance was measured in the O/C demand mode on the SUBMARINE PRODUCTS OXYMAX 3.

B. Controlled Parameters

1. Breathing Resistance Tests - Breathing resistance controlled parameters included:

(a) Standardized NEDU breathing rates, tidal volume, exhalation/inhalation time ratio and breathing waveform were controlled as set forth in NEDU Report 3-81 (reference 1).

(b) UBA breathing gas: pure O_2.

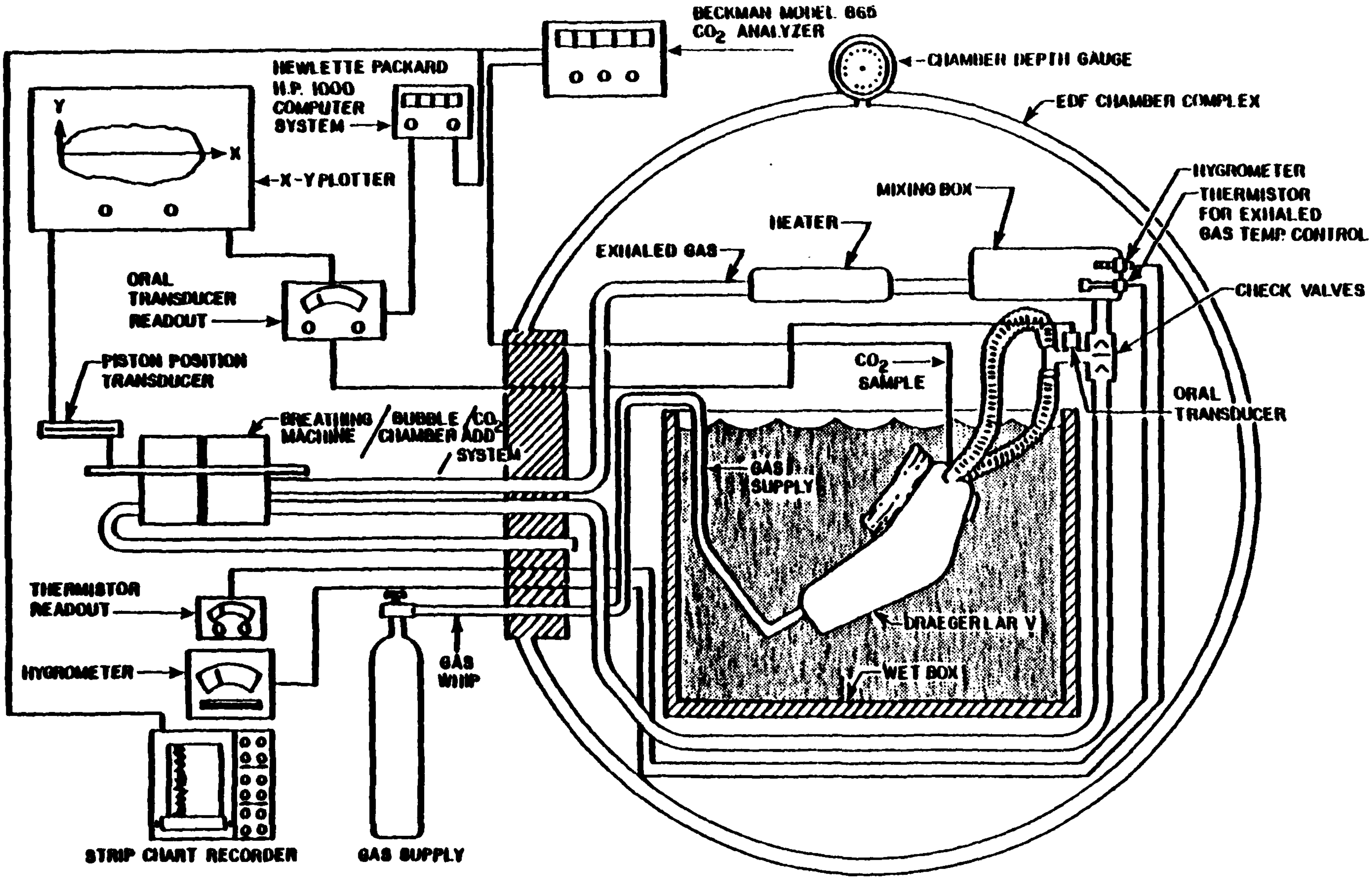
(c) Depths: 0, 15, 25 and 40 FSW.

(d) O_2 supply pressure: 1000 psig.

2. Canister Duration Tests - Canister duration controlled parameters included:

(a) Standardized CO_2 add rates and exhaled gas temperatures controlled as set forth in NEDU Report 3-81 (reference 1).

(b) UBA breathing gas: pure O_2.


BECKMAN MODEL 865
CO_2 ANALYZER
CHAMBER DEPTH GAUGE
EDF CHAMBER COMPLEX
HEWLETTE PACKARD
H.P. 1000
COMPUTER
SYSTEM
X-Y PLOTTER
Y
X
HYGROMETER
THERMISTOR
FOR EXHALED
GAS TEMP. CONTROL
MIXING BOX
HEATER
EXHALED GAS
CHECK VALVES
ORAL
TRANSDUCER
READOUT
CO_2
SAMPLE
ORAL
TRANSDUCER
PISTON POSITION
TRANSDUCER
BREATHING
MACHINE
BUBBLE
CHAMBER
CO_2
ADD
SYSTEM
GAS
SUPPLY
DRAEGER LAR V
WET BOX
THERMISTOR
READOUT
HYGROMETER
GAS
WHIP
STRIP CHART RECORDER
GAS SUPPLY

(c) CO_2 absorbent: HP SODASORB with moisture content between 13.5 and 15%.

(d) Water TEMP: 90, 70, 55, 40, 35 and 29°F.

(e) Relative humidity of exhaled gas: 90 ($\pm$ 2) %.

(f) Depths: 25 FSW.

(g) O_2 supply pressure: 1000 psig.

(h) Canister packing density: Canister duration in any UBA is quite sensitive to how the absorbent is packed. Consequently, great care was taken to assure uniformity of canister packing at $\pm$ 4 ounces in order to achieve consistent results.

C. Measured Parameters

1. Breathing Resistance Tests - Maximum ΔP in cm of H_2O (i.e. total pressure excursion between full exhalation and full inhalation cycles).

2. Canister Duration Tests: CO_2 level out of scrubber expressed as percentage of SEV.

D. Computed Parameters

1. Breathing Resistance Tests: Respiratory work per liter tidal volume measured in kg·m/l from ΔP vs volume plots. A typical pressure-volume plot is illustrated in Figure 2A.

2. Canister Duration Tests: Exhaled gas TEMP was calculated and controlled as a function of water temperature based on the standardized procedure set in NEDU Report 3-81 (reference 1).

E. Data Plotted

1. The following plots were developed from data obtained in the breathing resistance tests:

a. Breathing exhalation to peak inhalation ΔP vs depth at each RMV tested.

b. Respiratory work per liter vs depth at each RMV tested.

c. Respiratory work per liter vs RMV at each depth tested.

d. Peak inhalation and peak exhalation resistance vs depth at each RMV tested (OXYMAX 3 O/C mode only).

2. The following plots were developed from data obtained in the canister duration tests: canister effluent CO_2 (% SEV) vs time expressed as percent of SEV.

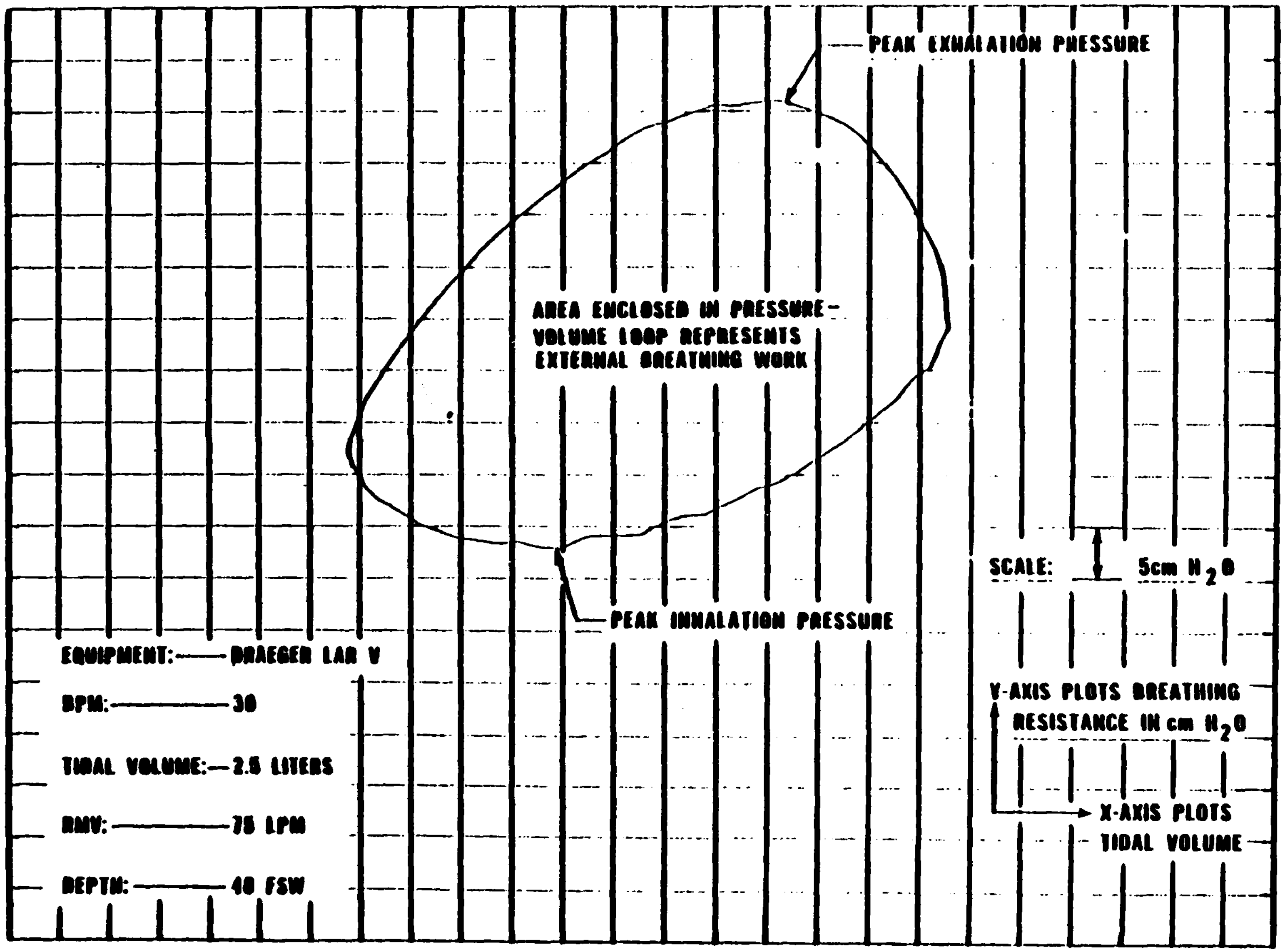


Figure 2A. Pressure – Volume Loop Generated at 75 RMV ...

V. RESULTS

A. Breathing Resistance & Respiratory Work

APPENDIX E (Figures 9 through 21) plot peak differential breathing pressures vs depth and APPENDIX F (Figures 22 through 37) plot breathing work vs depth for each UBA tested. Peak inhalation to peak exhalation in cmH_2O was measured at each RMV tested. Breathing work is measured in kg•m/l and is also plotted at each RMV evaluated.

Breathing work is a measure of the respiratory energy expended by the diver to operate his UBA. When used in conjunction with breathing resistance data, it provides a useful tool in the evaluation of UBA. TABLE 1 provides a comparison of the peak differential pressures in each UBA at 25 FSW and 75 RMV while TABLE 2 provides a similar comparison of breathing work for all six UBA. The numbers in parenthesis in TABLES 1 and 2 represent the relative position in which that particular UBA finished in each test (i.e., (1) would represent the best performance of the six units and (6) the worst).

B. CO2 Absorbent Canister Duration Tests

A total of 112 canister duration tests were conducted as part of this evaluation series. All canister duration tests were conductd at 25 FSW with ambient water temperature being varied from 29 to 90°F. A minimum of two runs were conducted at each set of conditions and whenever duration differences of more than 20 minutes were observed additional tests were performed. The mean canister durations for each UBA at all water temperatures are summarized in TABLE 3. The numbers in parenthesis in TABLE 3 represent the place in which that particular UBA finished in each test at each water temperature. At the bottom of TABLE 3, the number in parenthesis is a summation of the relative position scores at each water temperature. The lowest overall score will represent the canister with the longest overall durations.

Figure 38 is an example of the type of CO_2 absorbent canister duration plots generated during unmanned testing. Rest and work cycles are readily observed as continuing for the duration of each test. APPENDIX G (Figures 39-44) plot only the % SEV CO_2 vs time generated during the work cycles in order to display the results of testing each UBA at all temperatures on one graph. The data on each plot is carried beyond 0.50% SEV CO_2 during work cycles to give a more complete picture of UBA performance. The graphs stop at 0.88% SEV CO_2 due to limitations in the NEDU gas analysis equipment caused by the shallow test depth. Due to the large number of tests conducted only a representative plot for each set of test conditions with each UBA is shown.

C. Comparative Results

TABLE 4 provides a means of comparing breathing resistance, breathing work, canister duration and overall performance of the six UBA's tested. The numbers in TABLE 4 are the relative position scores for the

TABLE 1
Comparison of Total Breathing Resistance
Peak Inhalation to Peak Exhalation
Breathing Pressures at 25 FSW and 75 RMV

UBA	PEAK TO PEAK DIFFERENTIAL BREATHING PRESSURE	
AGA OXYDIVE	35	(2)
MODIFIED BIOPAK 240	23	(1)
DRAEGER LAR V	38	(3)
FENZY PO.68	38	(3)
OXYMAX 3 C/C (mouthpiece)	62	(6)
OXYMAX 3 C/C (FFM)	90	(7)
OXYMAX 3 O/C (O/C)	53	(5)
U.S. NAVY 'EMERSON'	47	(4)

TABLE 2
Comparison of Breathing Work
at 25 FSW and 75 RMV

UBA	BREATHING WORK (kg·m/l)	
AGA OXYDIVE	0.20	(2)
MODIFIED BIOPAK 240	0.15	(1)
DRAEGER LAR V	0.26	(3)
FENZY PO.68	0.26	(3)
OXYMAX 3 C/C (mouthpiece)	0.39	(5)
OXYMAX 3 C/C (FFM)	0.70	(6)
OXYMAX 3 O/C	0.39	(5)
U.S. NAVY 'EMERSON'	0.29	(4)

TABLE 3

Unmanned Canister Duration Tests
Summary of Results

WATER TEMP (°F)	AGA OXYDIVE	MOD BIOPAK 240	DRAEGER LAR V	FENZY PO.68	OXYMAX 3 C/C	U.S. NAVY 'EMERSON'
	MEAN TIME TO 0.5% CO2 SEV (MIN)					
29	(2) 74	(4) 39	(3) 54	(5) 31	(6) 9	(1) 91
35	(3) 74	(4) 49	(2) 78	(5) 36	(6) 7	(1) 102
40	(3) 65	(5) 34	(2) 80	(4) 36	(6) 12	(1) 110
55	(3) 84	(5) 58	(2) 120	(4) 67	(6) 12	(1) 144
70	(3) 116	(4) 108	(1) 157	(5) 88	(6) 31	(2) 154
90	(3) 143	(4) 115	(1) 168	(5) 98	(6) 56	(2) 162
SUMMATION OF RELATIVE POSITIONS	(21)	(28)	(17)	(34)	(47)	(16)

TABLE 4

Comparative Performance Scores

	AGA OXYDIVE	MOD BIOPAK 240	DRAEGER LAR V	FENZY PO.68	OXYMAX 3 C/C	U.S. NAVY 'EMERSON'
BREATHING RESISTANCE SCORE	2	1	3	3	6	4
WORK OF BREATHING SCORE	2	1	3	3	5	4
CANISTER DURATION SCORE	17	26	11	28	36	8
TOTAL SCORE	21	28	17	34	47	16
OVERALL FINISH	3	4	2	5	6	1

breathing resistance and breathing work tests and the summation of relative position scores for the canister duration tests at each water temperature. The total relative position score provides the total of all scores with the lowest score representing the UBA which had the highest unmanned performance overall. It is important to note that these scores are not statistically weighted (i.e., each test was regarded as being equally important).

VI. DISCUSSION

A. Breathing Resistance and Respiratory Work. NEDU Report 3-81, "Standardized NEDU Unmanned UBA Test Procedures and Performance Goals," (reference 1) establishes a performance goal of a total maximum breathing resistance of 22 cmH_2O and 0.18 kg m/l respiratory work at 75 RMV and maximum normal operating depth for C/C diver breath-driven UBA. This goal does not represent a minimum acceptable performance level. Rather, the goal when met by a UBA will insure that the UBA is not the limiting factor in diver performance.

The goal set forth in reference 1 is established as a function of depth and breathing mixture. Since O_2 UBA's are designed as inherently shallow water devices, the performance goal, which is described for C/C mixed gas rebreathers with a maximum operating depth of 150 FSW, is applied here at the maximum normal C/C O_2 UBA operating depth of 25 FSW.

Examination of the data presented in Tables 1 and 2 shows that none of the UBA tested met the established performance goal. However, manned testing as documented in reference 2 has proven that C/C O_2 UBA with performance similar to the DRAEGER LAR V will adequately support a hard working diver. Consequently, since the goals established in reference 1 are dynamic in nature, as more data is gathered, they will be updated to reflect the most recent and realistic performance requirements available.

The MODIFIED BIOPAK 240 exhibited the lowest breathing work and peak differential pressures measured during the evaluation. This was largely due to the use of an AGA mouthpiece and breathing hose assembly and an extremely shallow CO_2 absorbent canister design. The AGA mouthpiece and hoses were evaluated previously by NEDU and represent the state-of-the-art in high flow/low resistance design (see reference 3). However, the BIOPAK 240 is not specifically a UBA but a fire fighting equipment modified from a materials standpoint for U/W use and not currently in production for U/W applications. Additionally, manned testing of the MK 15 UBA, which has a back mounted breathing bag similar to the MOD BIOPAK 240, has revealed a significant comfort and off-gassing problem due to the hydrostatic pressure difference between the breathing bag and the divers mouthpiece or FFM in certain diver positions. This phenomena has not been observed to a significant degree in manned testing of chest mounted UBA.

Performance of the AGA OXYDIVE exceeded all others except for the BIOPAK 240. The AGA UBA also used the high flow/low resistance mouthpiece and hose assembly found on the BIOPAK 240. It should be noted that the AGA Corporation designed the OXYDIVE around a CO_2 absorbent material

manufactured to AGA specifications in the United Kingdom. When tested by NEDU with this special absorbent, its breathing work and peak differential breathing pressures were superior to all other UBA evaluated. However, since HP SODASORB is the only absorbent material approved for use by the U.S. Navy, all relevant comparisons between the AGA and other UBA must be made based on tests with HP SODASORB.

The DRAEGER LAR V, FENZY PO.68, and U.S. Navy EMERSON all exhibited similar performance. CO_2 absorbent canister design and smaller flow passages accounted for the breathing work and differential pressure values which were higher than those attained by the OXYDIVE and BIOPAK 240 (see Tables 1 and 2). As stated above, manned testing (reference 2) has shown performance for UBA with these work and differential pressure values to adequately support heavy work.

The SUBMARINE PRODUCTS OXYMAX 3 was tested for peak differential breathing pressure and breathing work in three modes: (1) C/C with a mouthpiece, (2) C/C with FFM and, (3) O/C with mouthpiece. At 22.5 and 40 RMV in the C/C with mouthpiece mode, peak to peak differential presures and respiratory work are comparable to the other UBA tested. However, 62.5 and higher RMV performance was significantly degraded due to canister design and small breathing passages. Performance decreased further when the OXYMAX 3 was used in conjunction with the SUBMARINE PRODUCTS FFM. Again, small breathing passages and check valves in the oral-nasal mask were the major contributing factors.

The OXYMAX 3 design of placing the O_2 demand valve in the mouthpiece provides a unique emergency O/C capability to this equipment. Performance in the O/C mode was comparable to that measured in the C/C with mouthpiece mode. However, breathing work at each RMV was higher than all but one of 36 SCUBA regulators tested during a comprehensive evaluation of commercial SCUBA regulators (reference 4) performed by NEDU in June 1979. Inadequate second stage venturi assist and small breathing passages and small mushroom valves are probable contributors to the OXYMAX 3 performance in the O/C mode. Figures 16 through 20 plot peak inhalation and peak exhalation differential pressures vs depth for each RMV tested in the O/C mode.

NEDU did not perform tests to determine the pressure differential required to initiate O_2 add from the UBA demand regulators. The set up is not conducive to this test and manned testing on a bicycle ergometer provides more comprehensive results.

B. CO2 Absorbent Canister Duration Tests

The standard NEDU unmanned canister duration test scenario as described in APPENDIX C was conducted. This procedure simulates a diver resting in the water on a bicycle-ergometer for 4 minutes at an O_2 consumption rate of 0.90 LPM and then working at an O_2 consumption rate of 1.60 LPM for 6 minutes. This routine is alternated until the canister output reaches a minimum level of 0.50% SEV CO_2. Canister durations are generally somewhat shorter during unmanned simulations than those actually experienced during manned evaluations. This is due to the unmanned CO_2 injection

rates, which simulate a man exhaling CO_2 laden gas into the UBA, being slightly higher than those actually measured on a man at rest or working in the water at 50 watts. However, the relative change in canister performance with varying water temperature will remain the same regardless of whether the test is manned or unmanned.

The EMERSON had canister durations comparable or superior to all UBA tested (see Table 3). The long cylindrical fiberglass canister used in the EMERSON holds ample absorbent material (see APPENDIX B) and is well suited, both from insulation and gas flow path standpoints, to diver breath-driven UBA use.

The DRAEGER LAR V exhibited canister durations similar to the EMERSON in warm water but at temperatures of 55°F and below the EMERSON canister lasted up to 37 minutes longer. While the construction and capacity of the LAR V canister is similar to the EMERSON, the oblong shape of the LAR V is not considered to be as efficient as the EMERSON.

Performance of the AGA OXYDIVE was similar, in general, to that of the LAR V. The AGA had longer durations in cold water than did the LAR V but in warm water the OXYDIVE was superior. At 35 and 29°F water temperatures the OXYDIVE had a mean canister duration which was 9 minutes longer than that measured at 40°F. This is not significant since variations of $\pm$ 10 minutes in canister durations under identical test conditions are normal, especially in cold water. It is important to stress again that the OXYDIVE radial flow canister was designed around a specific absorbent material manufactured to AGA specifications. NEDU performed canister duration tests with the OXYDIVE using this material and results were superior to all UBA tested, including the EMERSON, in all water temperatures. When used in the AGA, the special absorbent material produced canister durations which were virtually independent of water temperature. However, as with breathing resistance and breathing work testing, all relevant comparisons between the AGA and other UBA for U.S. Navy application must be made on the basis of HP SODASORB.

Mean canister duration times were similar in the FENZY PO.68 and the MODIFIED BIOPAK 240. Both UBA have metal or metal lined canisters and hold one pound less absorbent material than the DRAEGER or AGA units (see APPENDIX B). This combination of low thermal insulation and less absorbent material accounts for the shortened canister durations measured by NEDU. In addition, while the donut-shaped design of the REXNORD canister is similar to the U.S. Navy MK 15 and MK 16 UBA canisters, the BIOPAK 240 canister is extremely thin. As little as 4 to 6 ounces change in packing weight caused $\pm$ 1 hour change in canister duration times. Consistent canister duration times were impossible to achieve under identical test conditions due to the extreme sensitivity of the BIOPAK 240 canister to packing density.

The SUBMARINE PRODUCTS OXYMAX 3 exhibited canister durations which were significantly less than any other UBA tested (see Table 3). The OXYMAX 3 canister is uniquely located inside the UBA's breathing bag in order to better insulate it from cold water. However, the canister holds only 3.3 pounds of HP SODASORB. This coupled with its short, flat cylindrical design, does not allow sufficient dwell time for the exhaled gas passing through the

canister to be properly scrubbed of CO_2. SUBMARINE PRODUCTS LTD has developed a cold water modification for use with the OXYMAX 3 in water temperatures of 55°F or less. NEDU tested this modification and found that canister durations were increased by a factor of 2 to 1 over those recorded in Table 3 between 55 and 29°F.

VII. CONCLUSIONS

Of the six UBA tested, the REXNORD Modified BIOPAK 240 exhibited the least peak to peak differential breathing pressures and breathing work measured. However, short and inconsistent CO_2 absorbent canister durations demonstrated several serious shortcomings in the UBA design.

Breathing resistance/breathing work levels were similar between the AGA OXYDIVE and DRAEGER LAR V with the AGA unit being slightly superior. The AGA and DRAEGER units also significantly outperformed all other UBA, with the exception of the EMERSON, in the area of canister durations.

It is interesting to note that while the AGA OXYDIVE and DRAEGER LAR V are more compact and technically advanced than the EMERSON, the EMERSON came in first place in overall performance based on unmanned testing (see Table 4). This fact can provide important information as various design criteria are considered for future closed and semi-closed circuit UBA.

While exceeding the goals set in NEDU Report 3-81 (reference 1), manned testing indicates that both the AGA OXYDIVE, DRAEGER LAR V and EMERSON have breathing resistance/breathing work and canister durations which will adequately support a working diver at 25 FSW (reference 2).

VIII. REFERENCES

1. NEDU Report 3-81, 'Standardized NEDU Unmanned UBA Test Procedures and Performance Goals,' James R. Middleton and Edward D. Thalmann, CDR, MC, USN, July 1981.

2. NEDU Report 5-79, 'Evaluation of Modified DRAEGER LAR V Closed-Circuit Oxygen Rebreather,' James R. Middleton and Claude A. Piantadosi, August 1979.

3. NEDU Report 11-79, 'Unmanned Evaluation of U.S. Navy UBA EX-16 Prototype Closed Circuit Rebreather,' James R. Middleton, December 1979.

4. NEDU Report 2-80, 'Evaluation of Commercially Available SCUBA Regulators', James R. Middleton, March 1980.

APPENDIX A

List of Manufacturer Addresses

Model: AGA OXYDIVE

Manufacturer: AGA SPIRO AB
S-181 81 LIDINGO, Sweden
Tel. 08-731-1211

Model: BIOPAK 240

Manufacturer: REXNORD IND.
Great Valley Corporate Center
Malvern, PA 19355

Model: DRAEGER LAR V

Manufacturer: DRAGERWERK AG Lubeck
Diving Technics
Postfach 1339
Moislinger Allee 53/55
Lubeck 24
Federal Republic of Germany

Model: FENZY PO.68

Manufacturer: LA SPIROTECHNIQUE I.C.
INDUSTRIELLE ET COMMERCIALE
06510 Carros Industries (T)
France

American Distributor: U.S. Divers Company
3323 West Warner Avenue
Santa Ana, CA 92702

Model: OXYMAX 3

Manufacturer: SUBMARINE PRODUCTS LIMITED
Bridge End
Hexham
Northumberland NE464JP
England

Model: U.S. Navy C/C SCUBA (EMERSON)

Manufacturer: No longer manufactured

APPENDIX B

EQUIPMENT SPECIFICATIONS AND PHOTOS

A. AGA OXYDIVE (Figure 2)

Dimensions: 13.8 in. x 19.7 in. x 7.5 in.
Weight: 23 lb.
O_2 cylinder capacity: 10.6 cubic feet @ 3000 psig
CO_2 canister capacity: 5.0 lbs.
CO_2 canister material: fiberglass
Harness design: front-mounted, neck and waist straps
Breathing bag volume: 7 liters
O_2 supply pressure gauge: yes
Manual O_2 bypass valve: yes
O_2 add system type: demand valve located in breathing bag
Special features: the amount of O_2 metered on demand is adjustable

B. REXNORD BIOPAK 240 (Figure 3)

Dimensions: 14 in. x 19 in. x 8.8 in.
Weight: 24 lb.
O_2 cylinder capacity: 21 cubic feet @ 3000 psig
CO_2 canister capacity: 4.0 lbs.
CO_2 canister material: metal
Harness design: back-mounted, shoulder and waist straps
Breathing bag volume: 4 liters
O_2 supply pressure gauge: yes
Manual O_2 bypass valve: yes
O_2 add system type: demand valve located in breathing bag
Special features:
(1) Fire fighting apparatus modified for U/W use
(2) Utilized AGA mouthpiece and check valves

C. DRAEGER LAR V (Figure 4)

Dimensions: 11.8 in. x 16.7 in. x 6.7 in.
Weight: 24.2 lbs.
O_2 cylinder capacity: 10.6 $ft.^3$ @ 3000 psig
CO_2 canister capacity: 5.0 lbs.
CO_2 canister material: fiberglass
Harness design: front-mounted, neck and waist straps
Breathing bag volume: 6 liters
O_2 supply pressure gauge: yes
Manual O_2 bypass valve: yes
O_2 add system type: demand valve located in breathing bag

D. FENZY PO.68 (Figure 5)

Dimensions: 13.9 in. x 15.9 in. x 8 in.
Weight: 15.5 lbs.
O_2 cylinder capacity: 10 ft.^{3} @ 3000 psig
CO_2 canister capacity: 4.0 lbs.
CO_2 canister material: fiberglass lined with brass
Harness design: front-mounted, neck and waist straps
Breathing bag volume: 4 liters
O_2 supply pressure gauge: no
Manual O_2 bypass valve: no
O_2 add system type: demand valve located in breathing bag

E. OXYMAX 3 (Figure 6)

Dimensions: 13 in. x 15.74 in. x 7.1 in.
Weight: 15.5 lbs.
O_2 cylinder capacity: 14.12 ft.^{3} @ 3000 psig
CO_2 canister capacity: 3.3 lbs.
CO_2 canister material: fiberglass
Harness design: front-mounted, neck and waist straps
Breathing bag volume: 5 liters
O_2 supply pressure gauge: yes
Manual O_2 bypass valve: yes
O_2 add system type: demand valve located in mouthpiece
Special features:
  (1) Has ability to be used as O/C demand SCUBA in emergencies
  (2) Unit may be used with FFM or mouthpiece
  (3) CO_2 absorbent canister is located inside the breathing bag for insulation

F. U.S. Navy C/C SCUBA (EMERSON) (Figures 7 & 7A)

Dimensions: 12 in. x 22.5 in. x 5 in.
Weight: 35 lbs.
O_2 cylinder capacity: 12.7 ft.^{3} @ 2000 psig
CO_2 canister capacity: 4.5 lbs.
CO_2 canister material: fiberglass
Harness design: back-mounted, harness integrated with breathing bags
Breathing bag volume: 8 liters (2 bags)
O_2 supply pressure gauge: yes
Manual O_2 bypass valve: yes
O_2 add system type: adjustable constant flow orifice located in control block on the lower right breathing bag

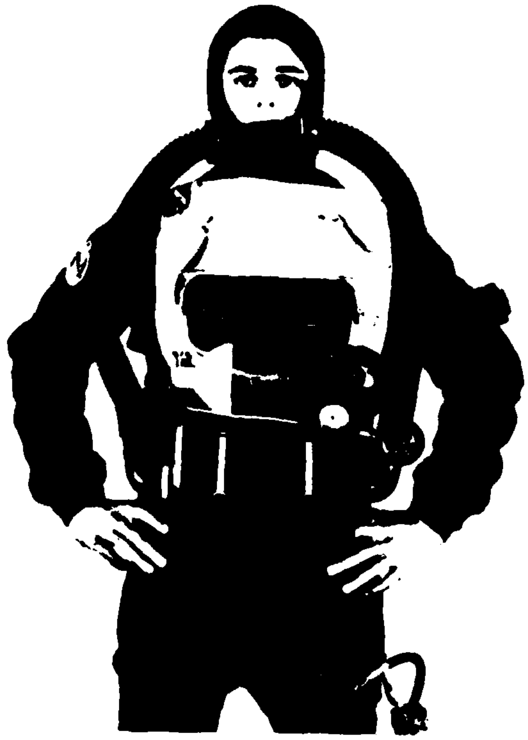


Figure 3. AGA OXYDIVE

Figure 4. REXNORD BIOPAK 240

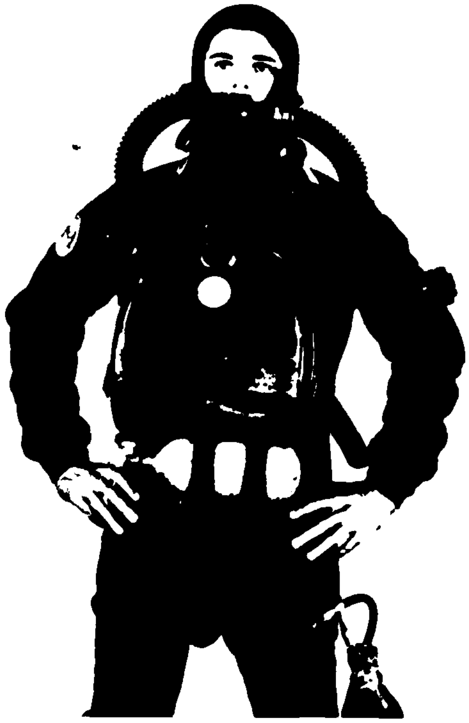


Figure 5. DRAEGER LAR V

Figure 6. FENZY PO.68

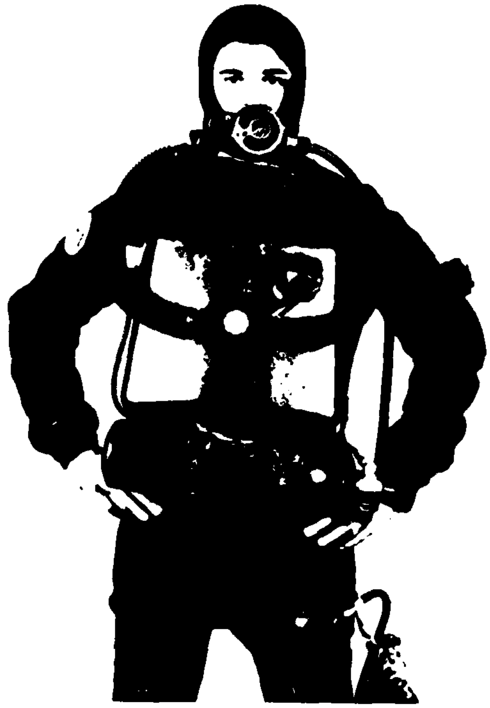


Figure 7. OXYMAX 3

Figure 8. U. S. C/C SCUBA (EMERSON), Front View

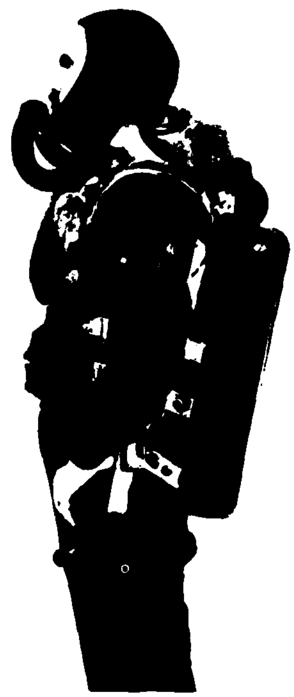


Figure 8A. Side View

APPENDIX C

Test Plan

A. Test plan for breathing resistance evaluation:

(1) (a) Insure that O_2 UBA is set to manufacturers specification and is working properly.

(b) Chamber on surface.

(c) Calibrate transducers.

(d) Open make-up gas supply valve to test UBA.

(e) Adjust breathing machine to 1.5 l tidal volume and 15 BPM and take readings.

(f) Adjust breathing machine to 2.0 l tidal volume and 20 BPM and take readings.

(g) Adjust breathing machine to 2.5 l tidal volume and 25 BPM and take readings.

(h) Adjust breathing machine to 2.5 l tidal volume and 30 BPM and take readings.

(i) Adjust breathing machine to 3.0 l tidal volume and 30 BPM and take readings.

(j) Stop breathing machine.

(2) (a) Pressurize chamber to 15, 25 and 40 FSW.

(b) Repeat steps (1)(e) - (1)(j) at each depth.

(3) (a) Bring chamber to surface.

(b) Check calibration on transducers.

(4) Repeat steps (1) - (5) with other UBAs and mouthpiece and face mask assembly, as applicable.

B. Test plan for CO_2 canister duration evaluation:

(1) (a) Insure that O_2 UBA is set to factory specifications and is working properly using HP SODASORB.

(b) Chamber is on surface.

(c) Calibrate transducers and CO_2 analyzers.

(d) Open make-up gas supply valve to test UBA.

(e) Water TEMP to be approximately 90°F.

(f) Start humidity add system.

(g) Pressurize chamber to 25 FSW.

(h) Start CO_2 add and maintain following procedure until 1.0% SEV CO_2 is reached:

4 minutes at 0.9 LPM CO_2 add/2.0 l tidal volume and 11.5 BPM.

6 minutes at 2.0 LPM CO_2 add/2.0 l tidal volume and 25 BPM.

(i) Take data every 30 seconds to breakthrough.

(2) Repeat steps (1)(a) - (1)(i) at 70, 55, 40, 35 and 29°F, respectively.

APPENDIX D

Test Equipment

1. Breathing Machine.

2. VALIDYNE DP-15 pressure transducer w/1.00 psid diaphragm (oral pressure) (1 ea).

3. Wet test box.

4. The EDF heating and cooling system will be used to control water temperature during the canister duration tests.

5. MFE Model 715M X-Y plotter.

6. VALIDYNE CD-19 transducer readout (1 ea).

7. External O_2 supply pressure gauge.

8. Chamber depth gauge.

9. Test UBAs.

10. Breathing machine/piston position transducer/CO_2 and humidity-add system.

11. Relative humidity sensor.

12. Strip chart recorder.

13. Thermistor for inhaled gas TEMP (1 ea).

14. DIGITEC HT-5820 Thermistor readouts (3 ea).

15. BECKMAN 865 Infrared Analyzers for monitoring CO_2 out of the scrubber (2 ea).

16. HEWLETT-PACKARD Model HP 1000 Computer System.

APPENDIX E

Breathing Resistance Data

Peak inhalation to peak exhalation differential pressure vs depth is plotted for all six UBAs tested. Peak inhalation and peak exhalation resistances vs depth are plotted for the OXYMAX 3 in the open circuit mode only.

KEY:

Figure 9	: AGA OXYDIVE
Figure 10	: MODIFIED BIOPAK 240
Figure 11	: DRAEGER LAR V
Figure 12	: FENZY PO. 68
Figure 13	: OXYMAX 3, CLOSED-CIRCUIT MODE
Figure 14	: OXYMAX 3, FULL FACE MASK, CLOSED-CIRCUIT MODE
Figure 15	: OXYMAX 3, OPEN-CIRCUIT MODE
Figure 16	: OXYMAX 3, OPEN-CIRCUIT DEMAND MODE
Figure 17	: OXYMAX 3, OPEN-CIRCUIT DEMAND MODE
Figure 18	: OXYMAX 3, OPEN-CIRCUIT DEMAND MODE
Figure 19	: OXYMAX 3, OPEN-CIRCUIT DEMAND MODE
Figure 20	: OXYMAX 3, OPEN-CIRCUIT DEMAND MODE
Figure 21	: U.S. NAVY CLOSED-CIRCUIT SCUBA (EMERSON)

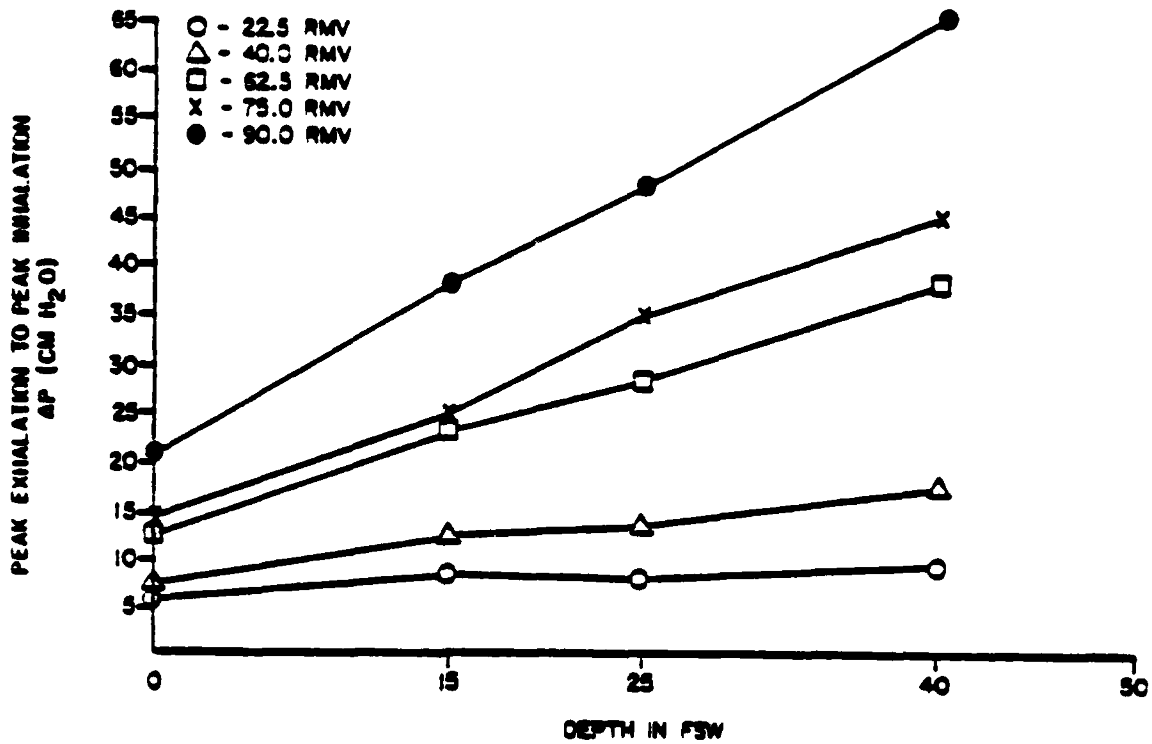


Figure 9. AGA OXYDIVE
PEAK DIFFERENTIAL PRESSURES vs. DEPTH

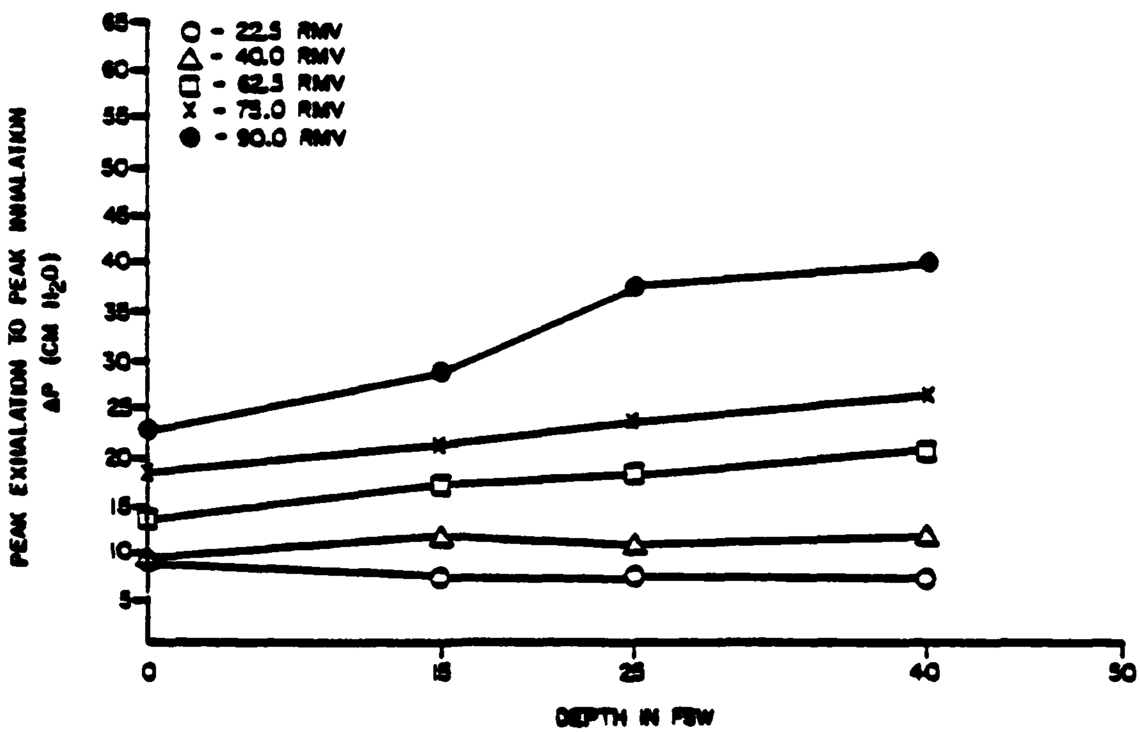


Figure 10. MODIFIED BIOPAK 240
PEAK DIFFERENTIAL PRESSURES vs. DEPTH

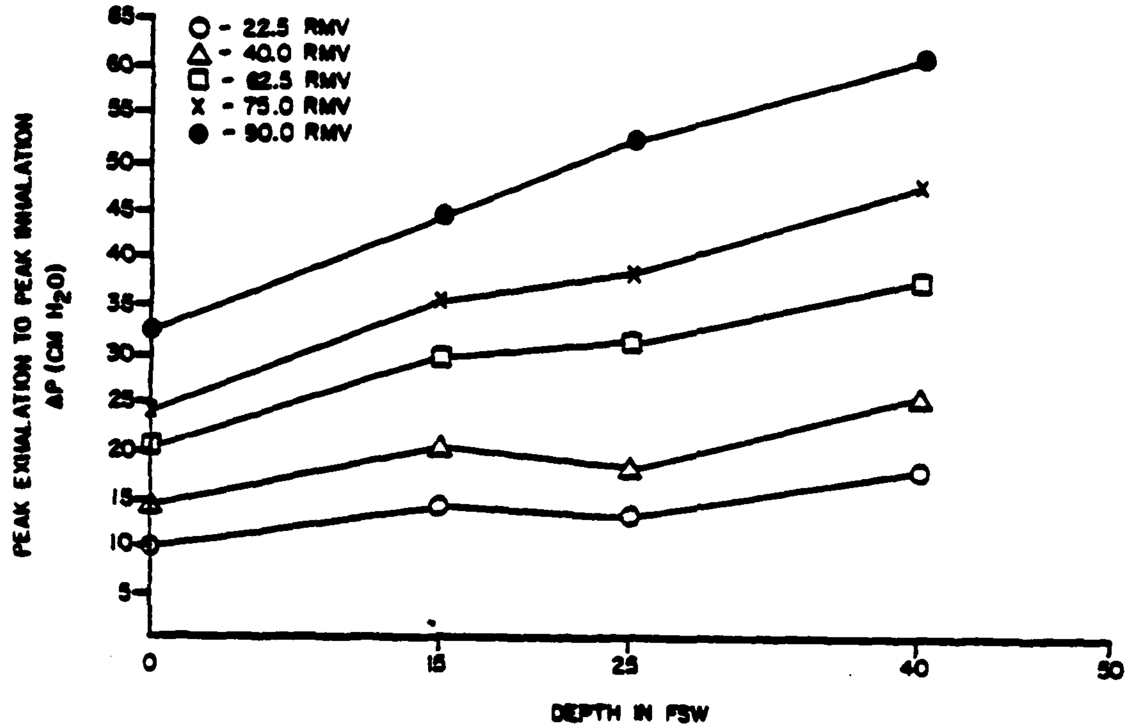


Figure 11. DRAEGER LAR V
PEAK DIFFERENTIAL PRESSURES vs. DEPTH

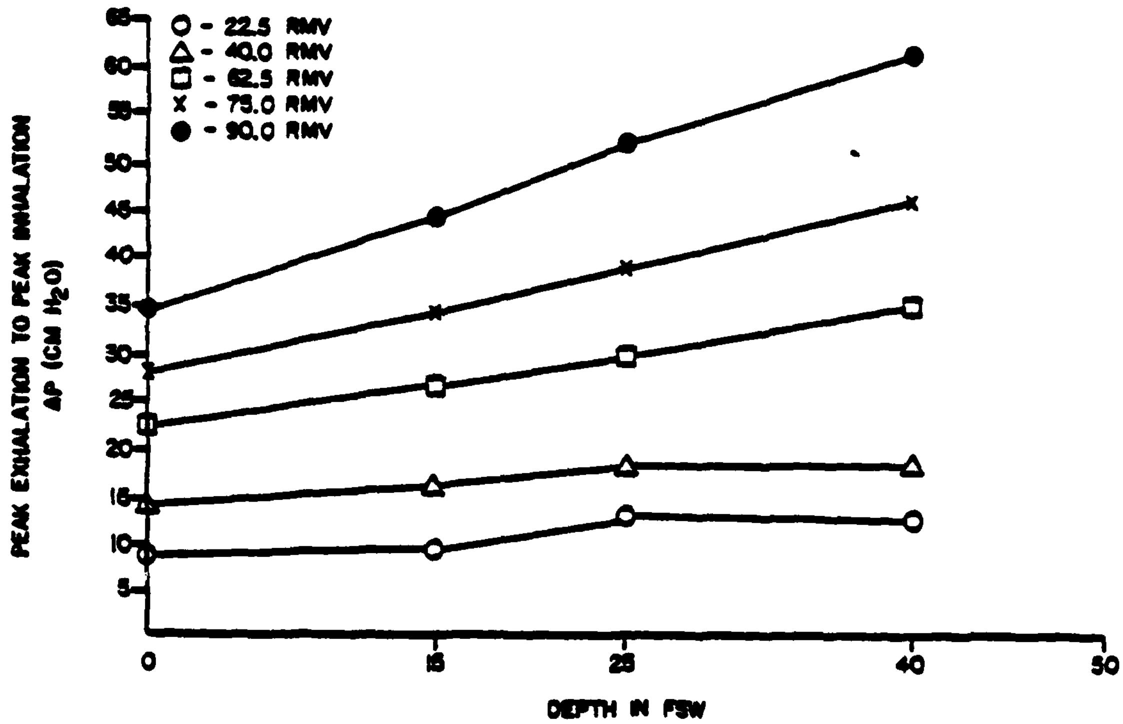


Figure 12. FENZY PO. 68
PEAK DIFFERENTIAL PRESSURES vs. DEPTH

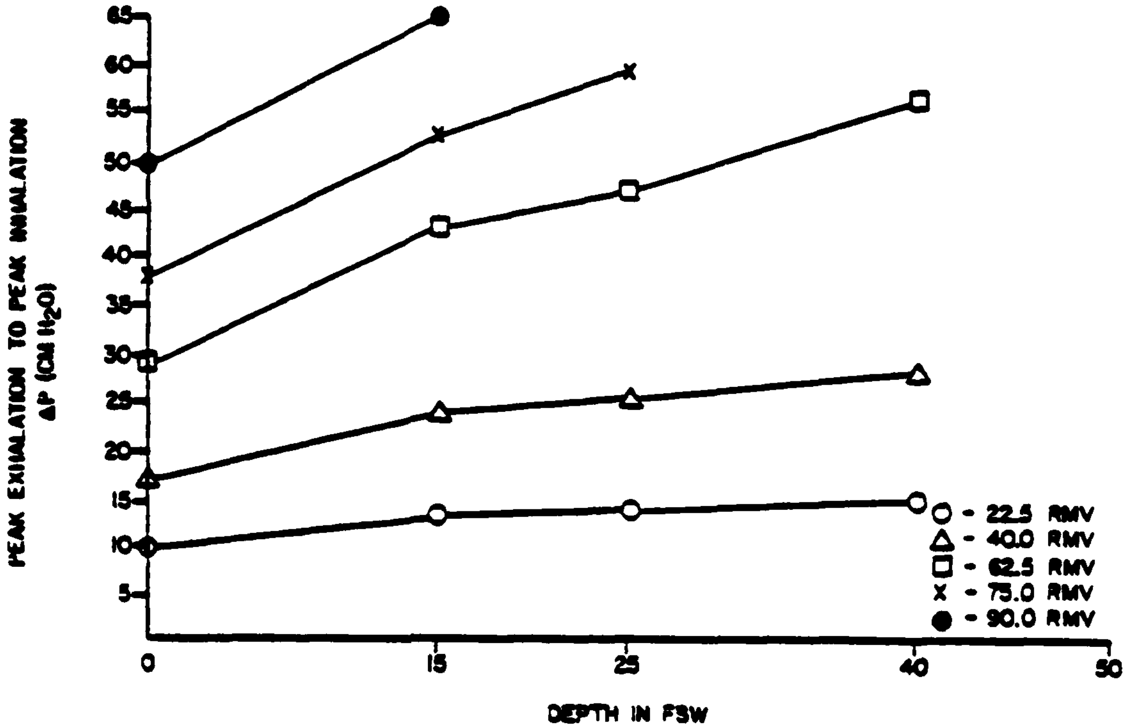


Figure 13. OXYMAX 3, CLOSED-CIRCUIT MODE
PEAK DIFFERENTIAL PRESSURES vs. DEPTH

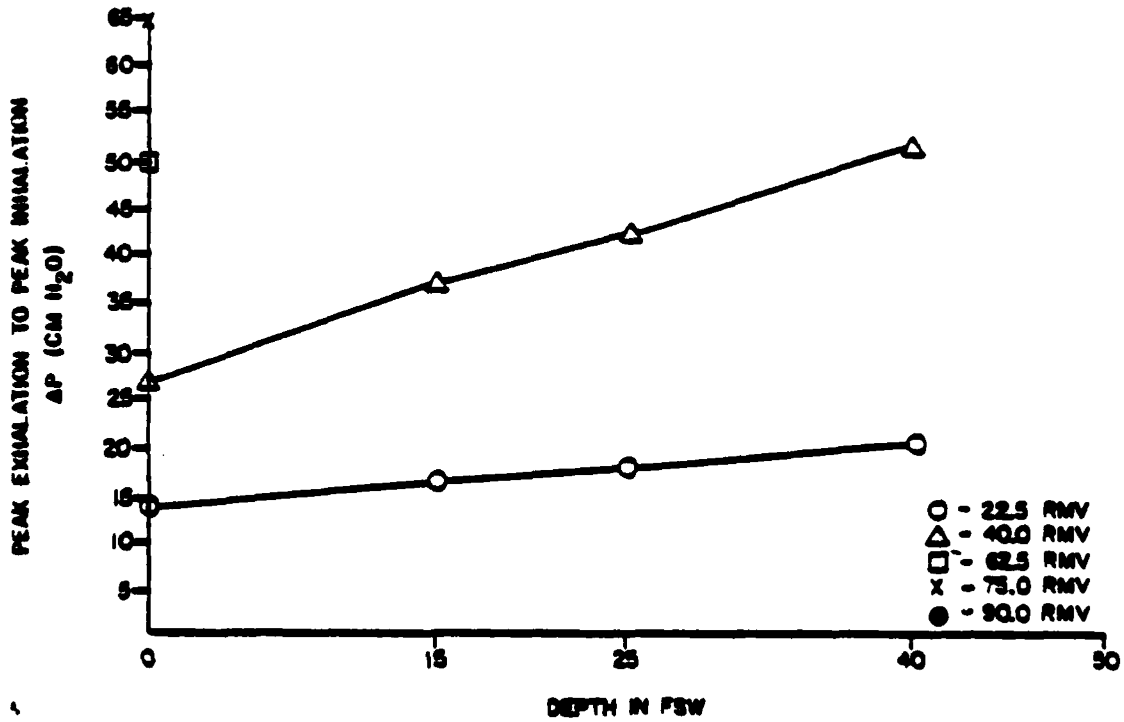


Figure 14. OXYMAX 3, FULL FACE MASK, CLOSED-CIRCUIT MODE
PEAK DIFFERENTIAL PRESSURES vs. DEPTH

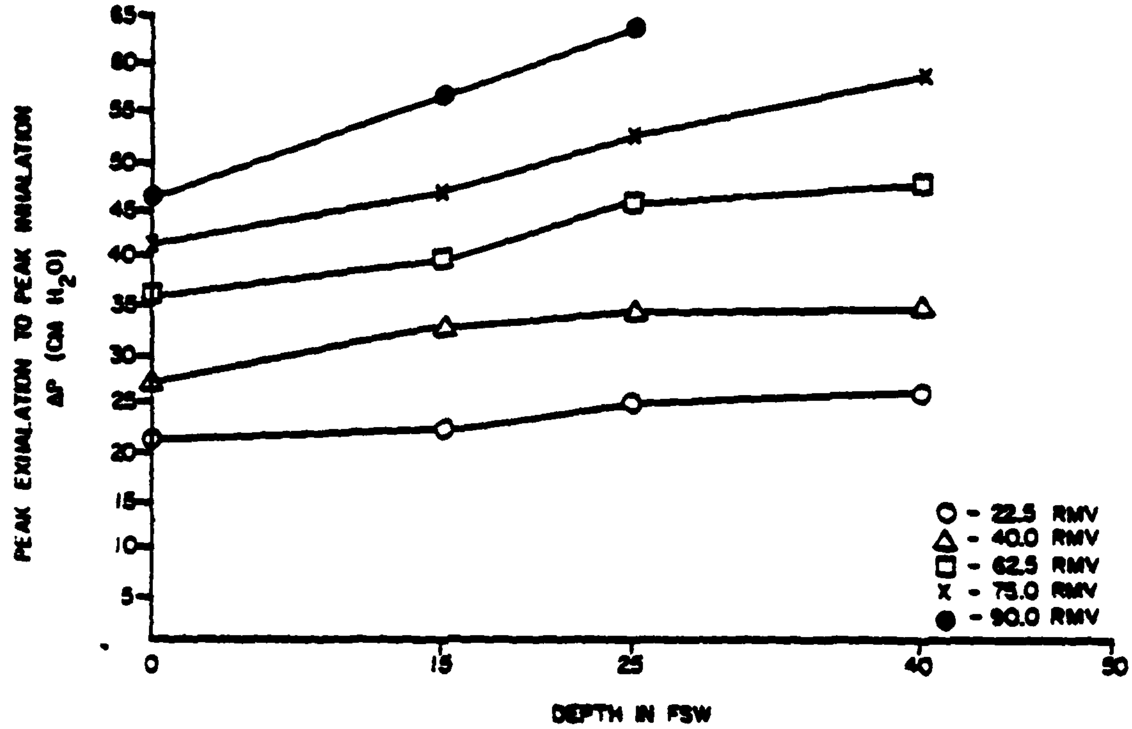


Figure 15. OXYMAX 3, OPEN-CIRCUIT MODE
PEAK DIFFERENTIAL PRESSURES vs. DEPTH

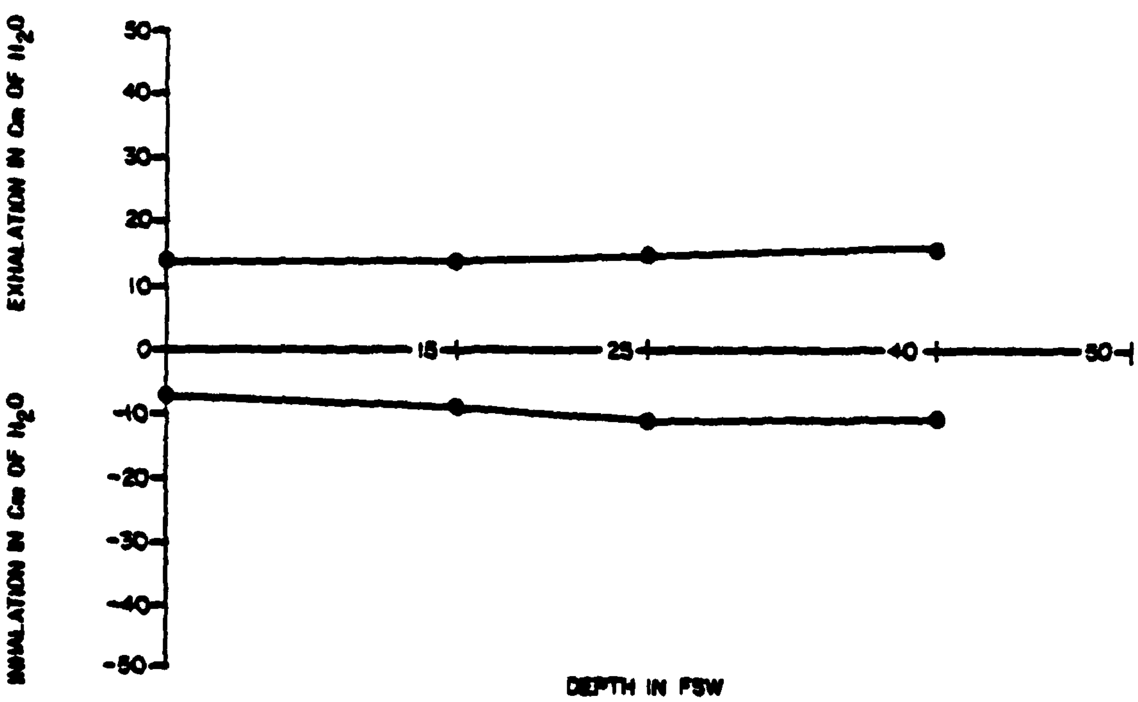


Figure 16. OXYMAX 3, OPEN-CIRCUIT DEMAND MODE
PEAK DIFFERENTIAL PRESSURES vs. DEPTH AT 22.5 RMV

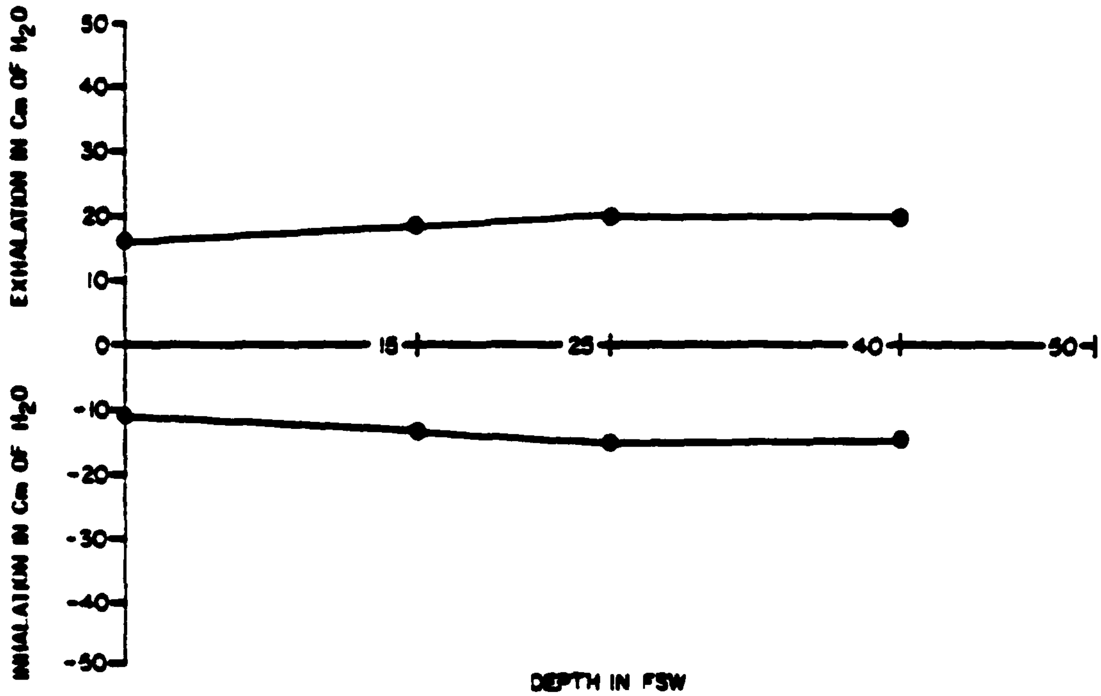


Figure 17. OXYMAX 3, OPEN-CIRCUIT DEMAND MODE
PEAK DIFFERENTIAL PRESSURES vs. DEPTH AT 40.0 RMV

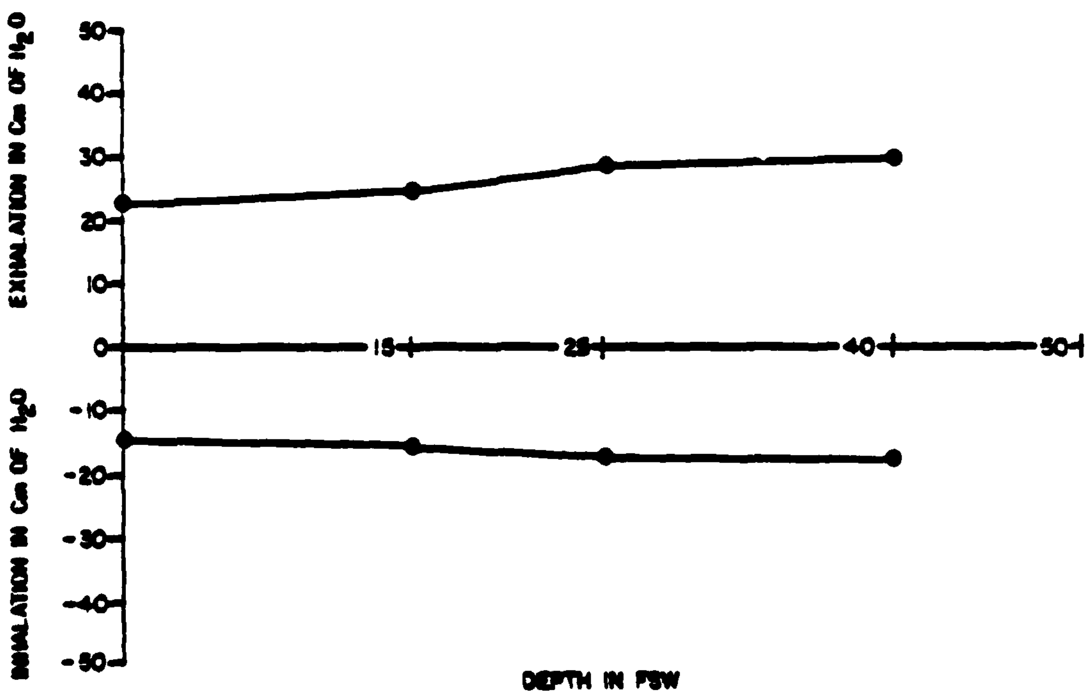


Figure 18. OXYMAX 3, OPEN-CIRCUIT DEMAND MODE
PEAK DIFFERENTIAL PRESSURES vs. DEPTH AT 62.5 RMV

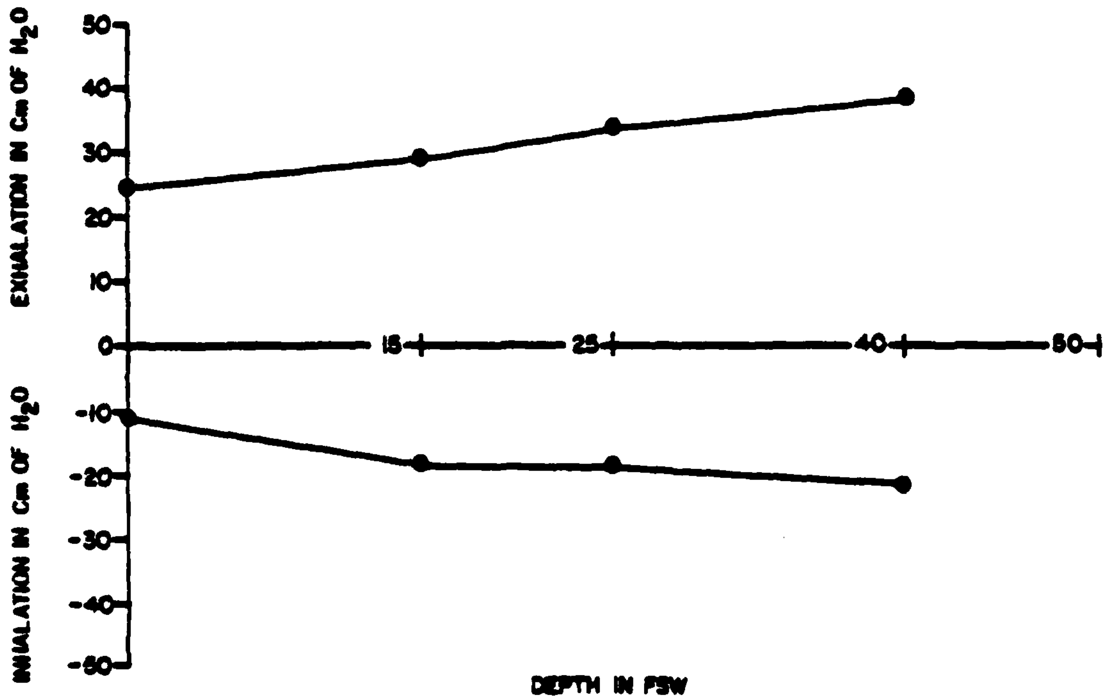


Figure 19. OXYMAX 3, OPEN-CIRCUIT DEMAND MODE
PEAK DIFFERENTIAL PRESSURES vs. DEPTH AT 75.0 RMV

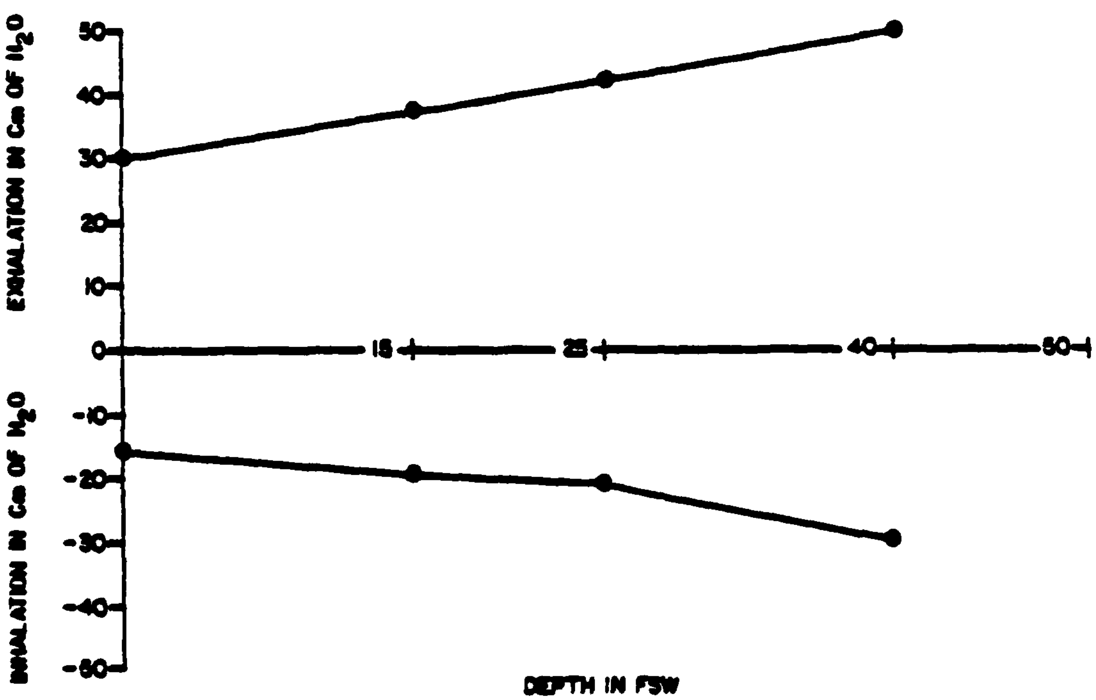


Figure 20. OXYMAX 3, OPEN-CIRCUIT DEMAND MODE
PEAK DIFFERENTIAL PRESSURES vs. DEPTH AT 90.0 RMV

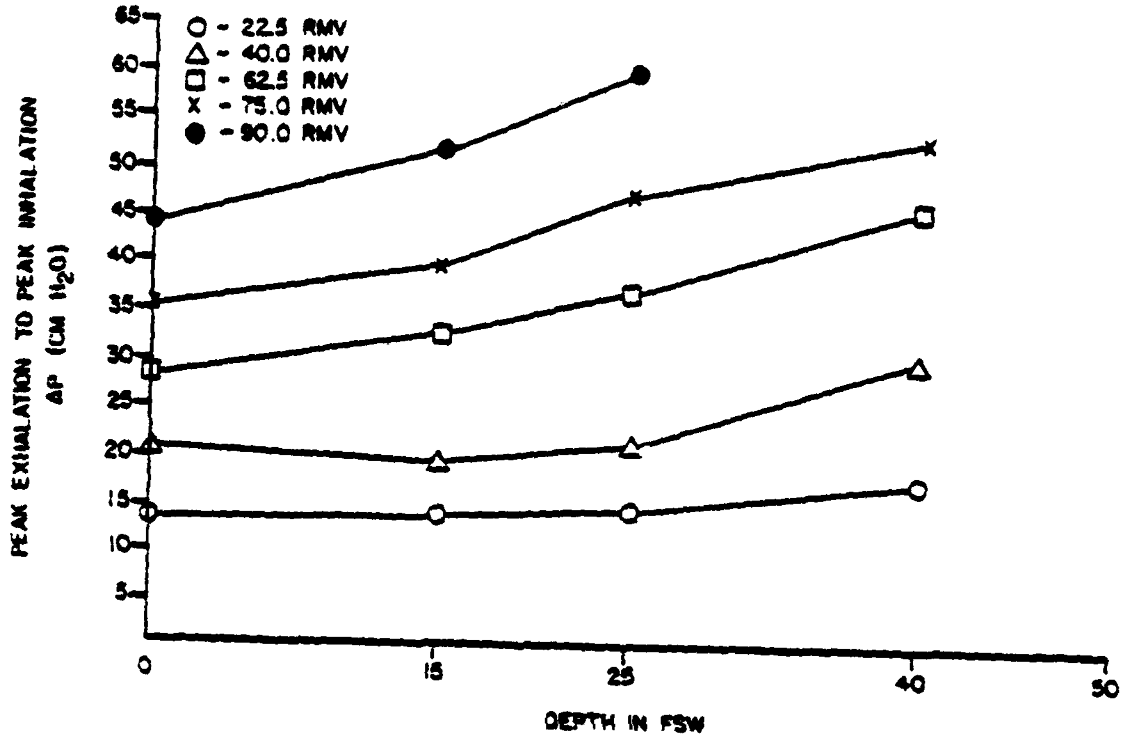


Figure 21. U.S. NAVY CLOSED-CIRCUIT SCUBA (EMERSON)
PEAK DIFFERENTIAL PRESSURES vs. DEPTH

APPENDIX F

Breathing Work Data

Total respiratory work vs depth at each RMV tested and total respiratory work vs RMV at each depth tested are plotted in this section.

KEY:

Figures 22 through 23 : AGA OXYDIVE

Figures 24 through 25 : MODIFIED BIOPAK 240

Figures 26 through 27 : DRAEGER LAR V

Figures 28 through 29 : FENZY PO.68

Figures 30 through 31 : OXYMAX 3, CLOSED-CIRCUIT w/mouthpiece

Figures 32 through 33 : OXYMAX 3, CLOSED-CIRCUIT w/FFM

Figures 34 through 35 : OXYMAX 3, OPEN-CIRCUIT

Figures 36 through 37 : U.S. NAVY CLOSED-CIRCUIT SCUBA (EMERSON)

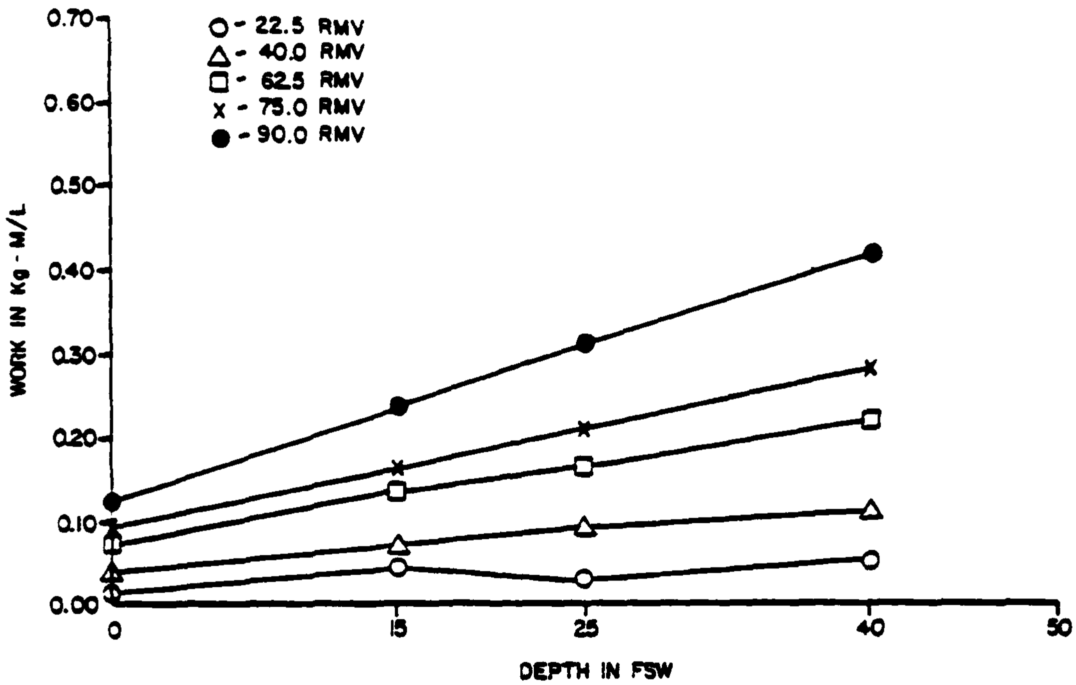


Figure 22. AGA OXYDIVE
BREATHING WORK vs. DEPTH

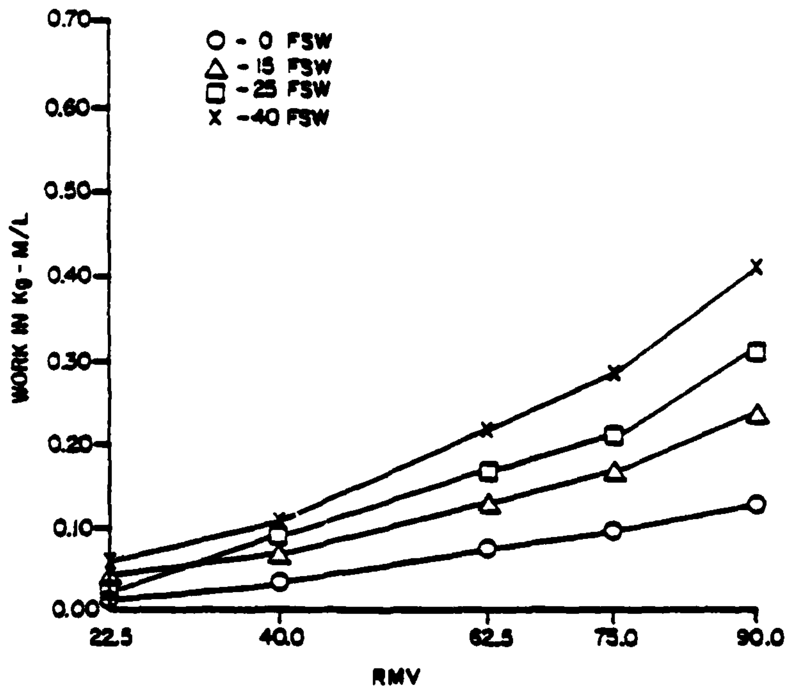


Figure 23. AGA OXYDIVE
BREATHING WORK vs. RMV

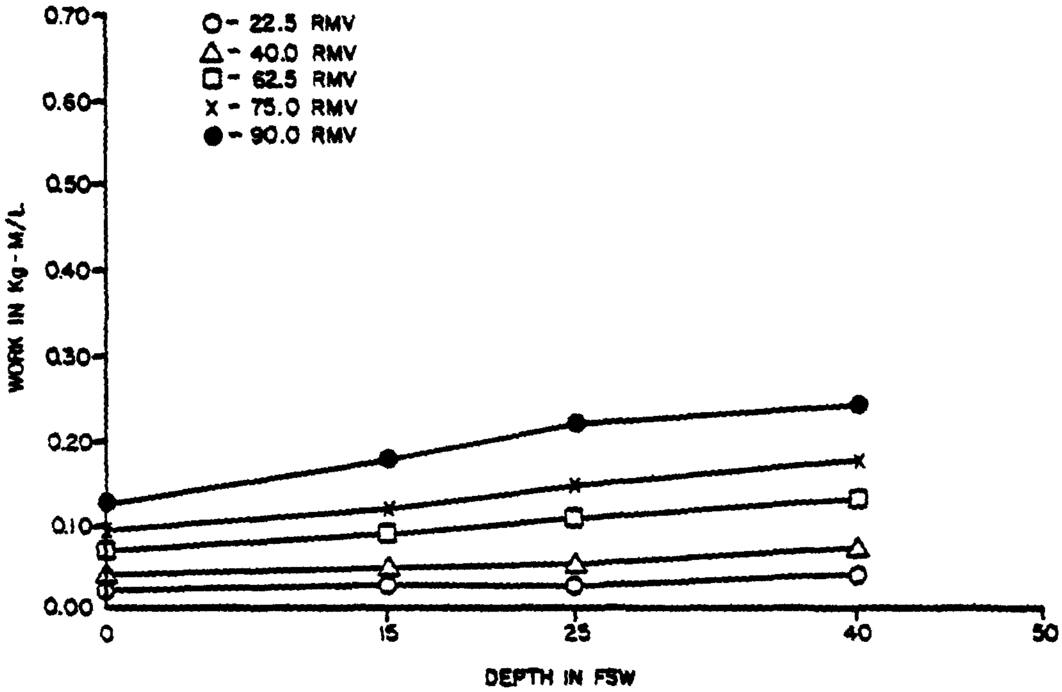


Figure 24. MODIFIED BIOPAC 240
BREATHING WORK vs. DEPTH

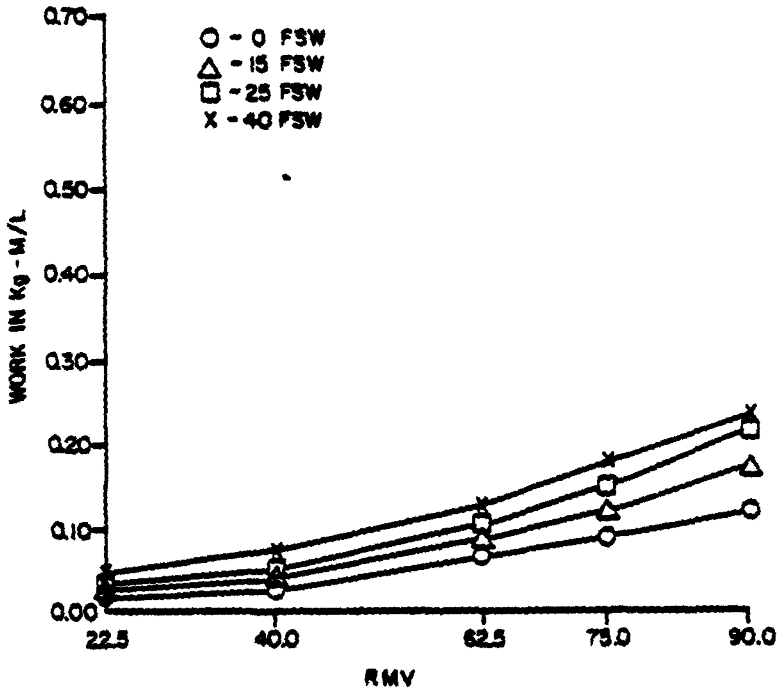


Figure 25. MODIFIED BIOPAC 240
BREATHING WORK vs. RMV

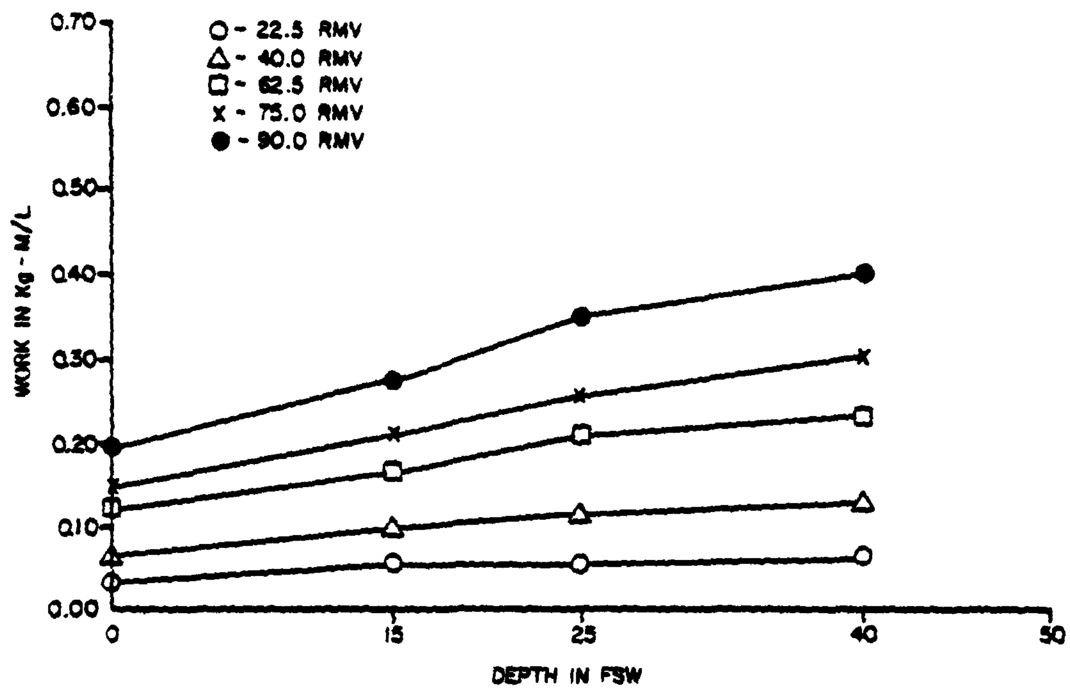


Figure 26. DRAEGER LAR V
BREATHING WORK vs. DEPTH

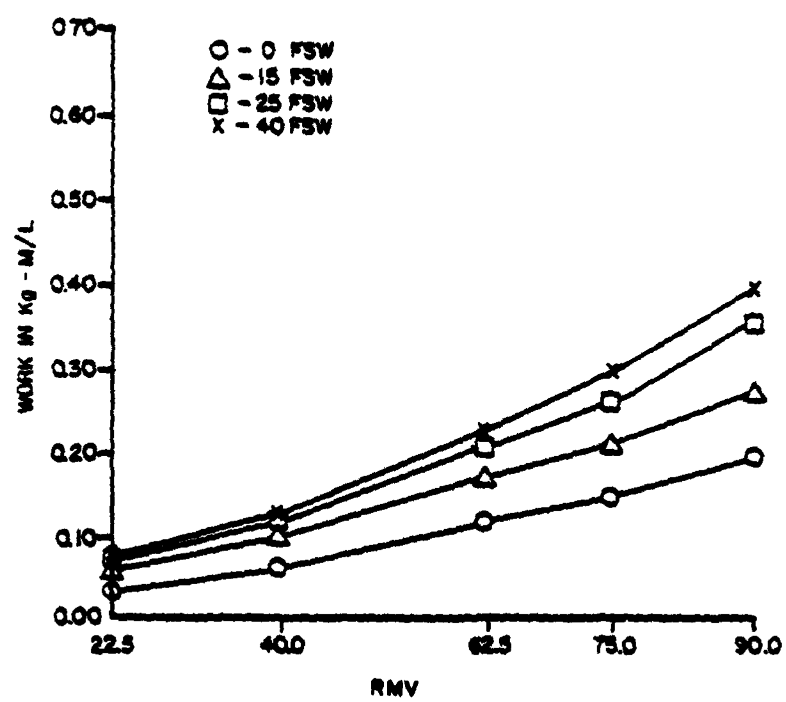


Figure 27. DRAEGER LAR V
BREATHING WORK vs. RMV

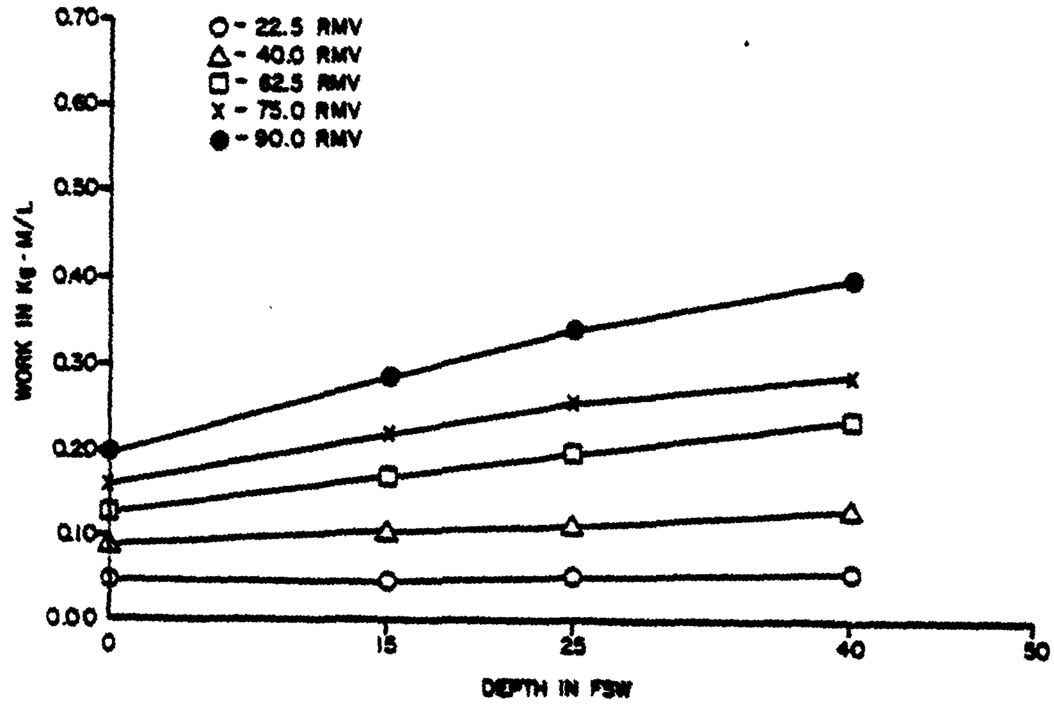


Figure 28. FENZY PO. 68
BREATHING WORK vs. DEPTH

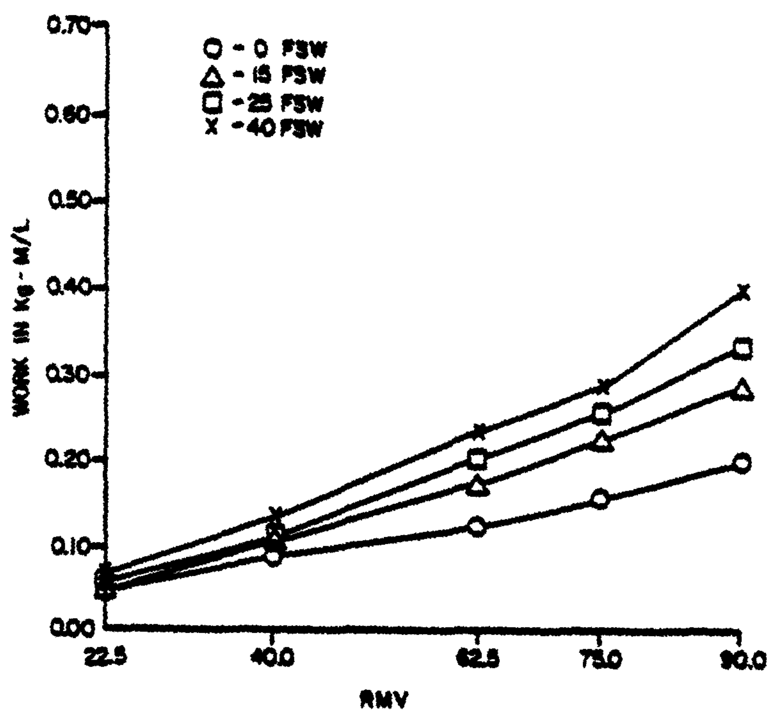


Figure 29. FENZY PO. 68
BREATHING WORK vs. RMV

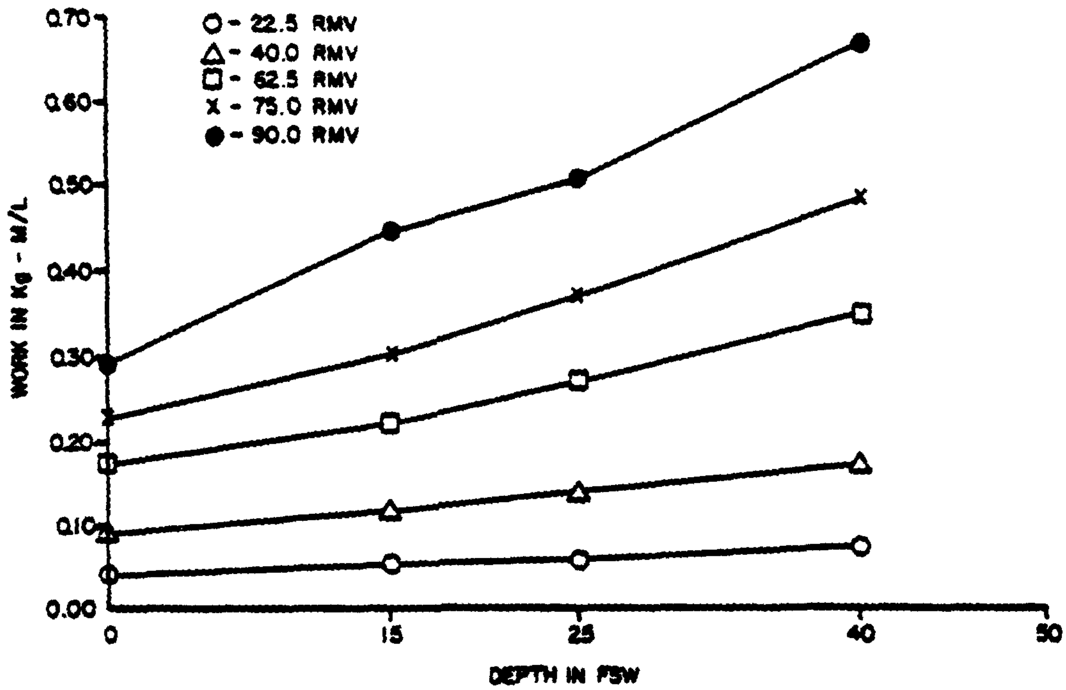


Figure 30. OXYMAX 3, CLOSED-CIRCUIT MODE
BREATHING WORK vs. DEPTH

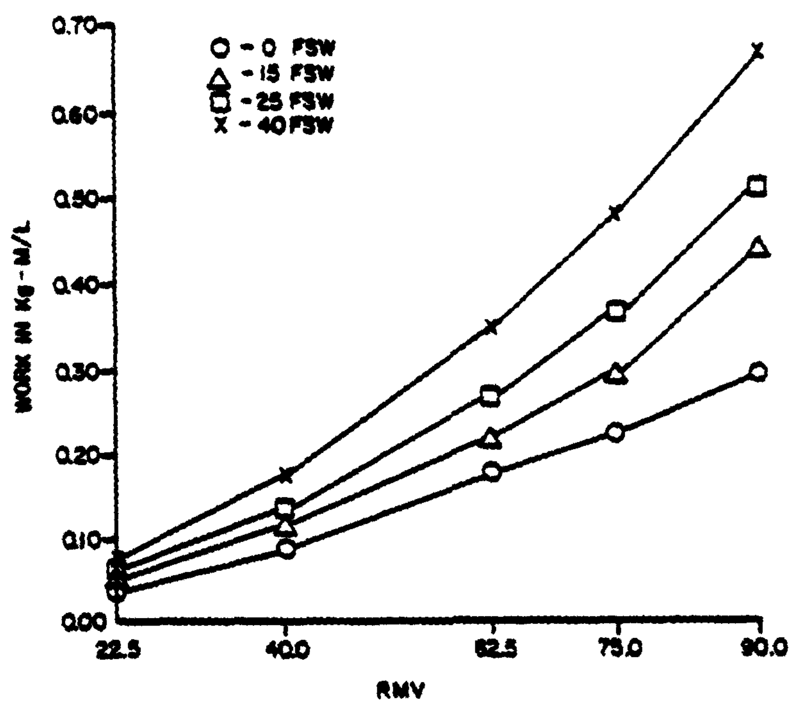


Figure 31. OXYMAX 3, CLOSED-CIRCUIT MODE
BREATHING WORK vs. RMV

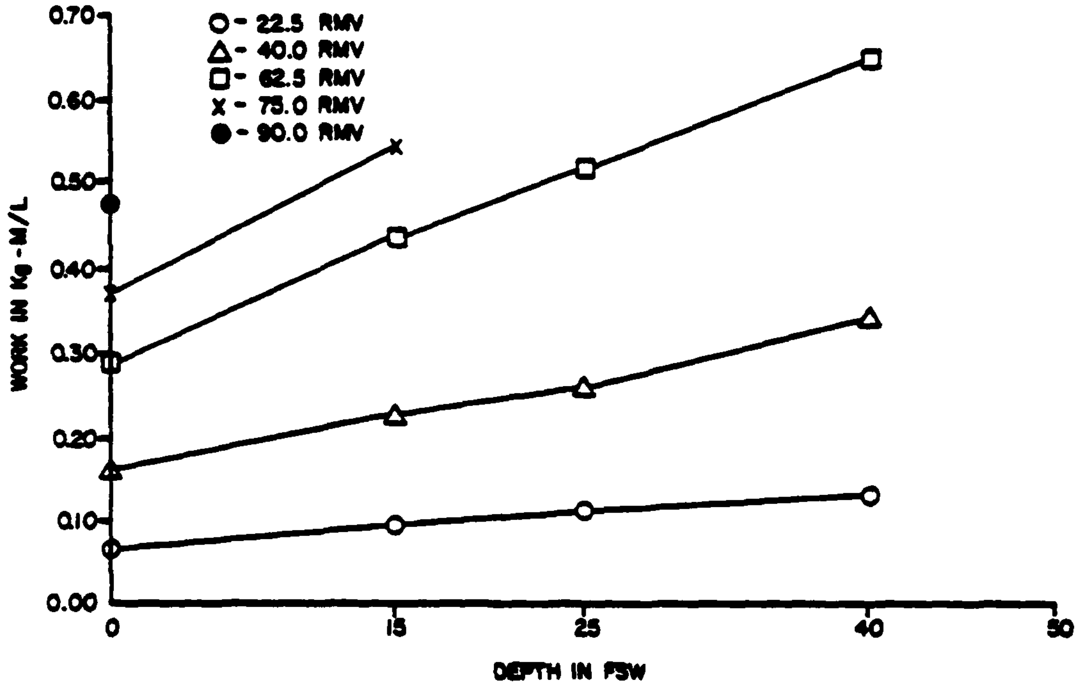


Figure 32. OXYMAX 3, FULL FACE MASK, CLOSED-CIRCUIT MODE BREATHING WORK vs. DEPTH

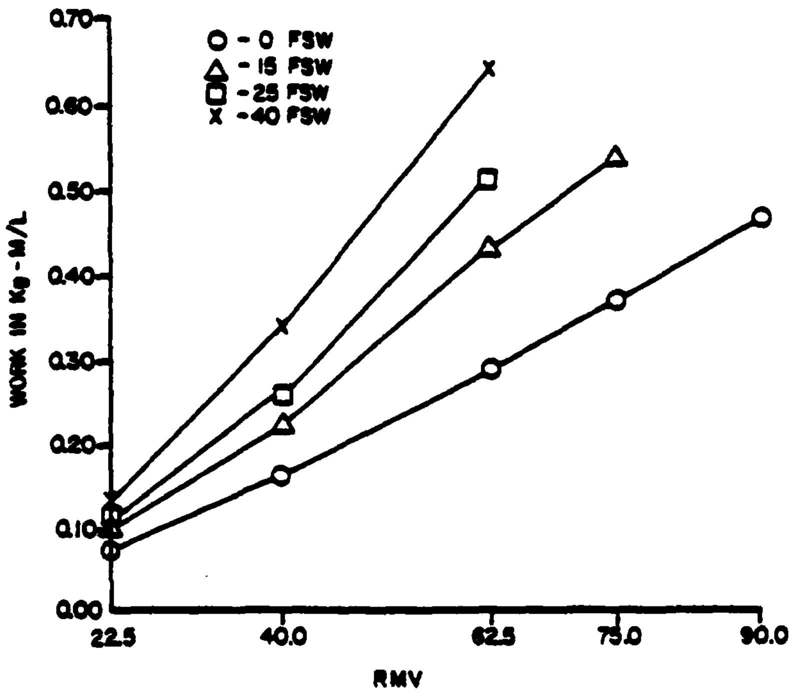


Figure 33. OXYMAX 3, FULL FACE MASK, CLOSED-CIRCUIT MODE BREATHING WORK vs. RMV

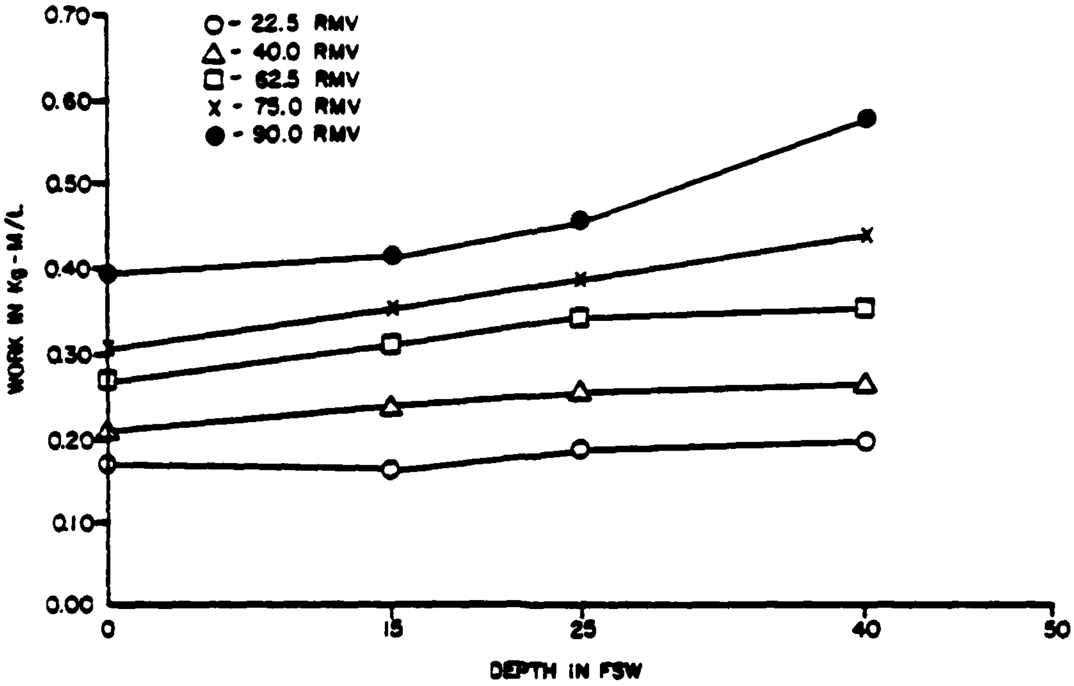


Figure 34. OXYMAX 3, OPEN-CIRCUIT MODE
BREATHING WORK vs. DEPTH

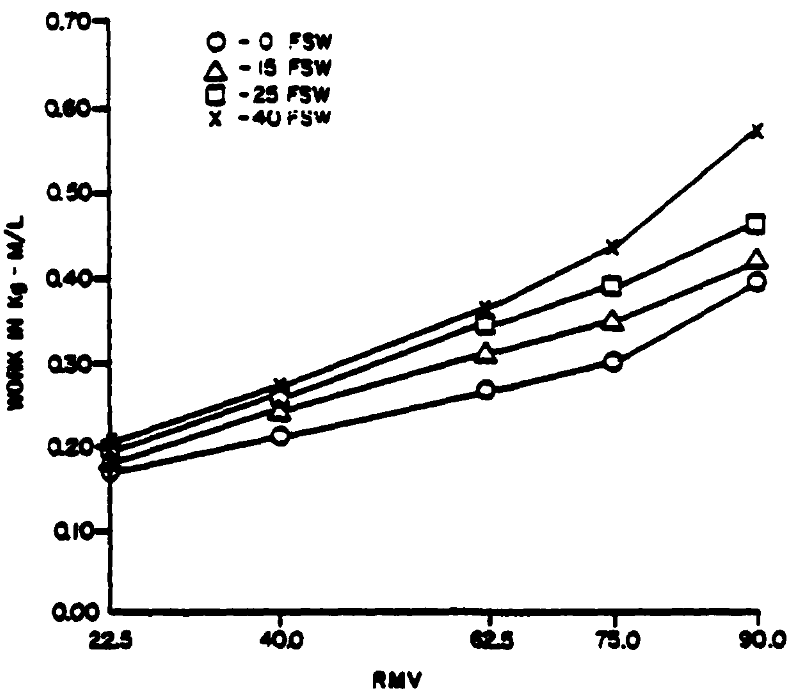


Figure 35. OXYMAX 3, OPEN-CIRCUIT MODE
BREATHING WORK vs. RMV

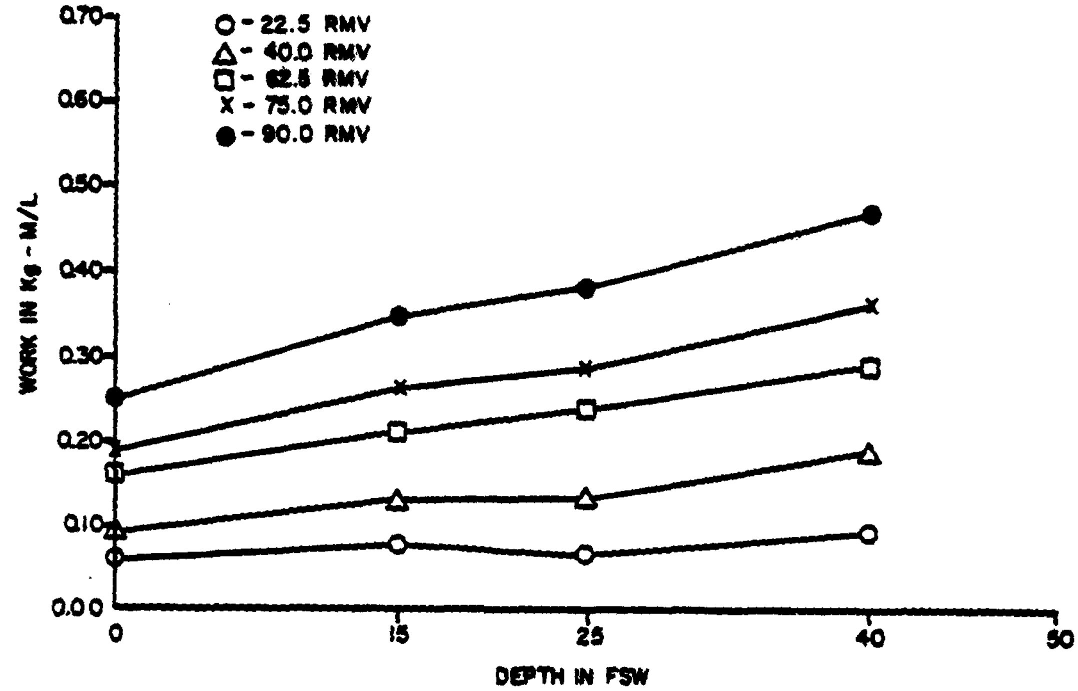


Figure 36. U.S. NAVY CLOSED-CIRCUIT SCUBA (EMERSON) BREATHING WORK vs. DEPTH

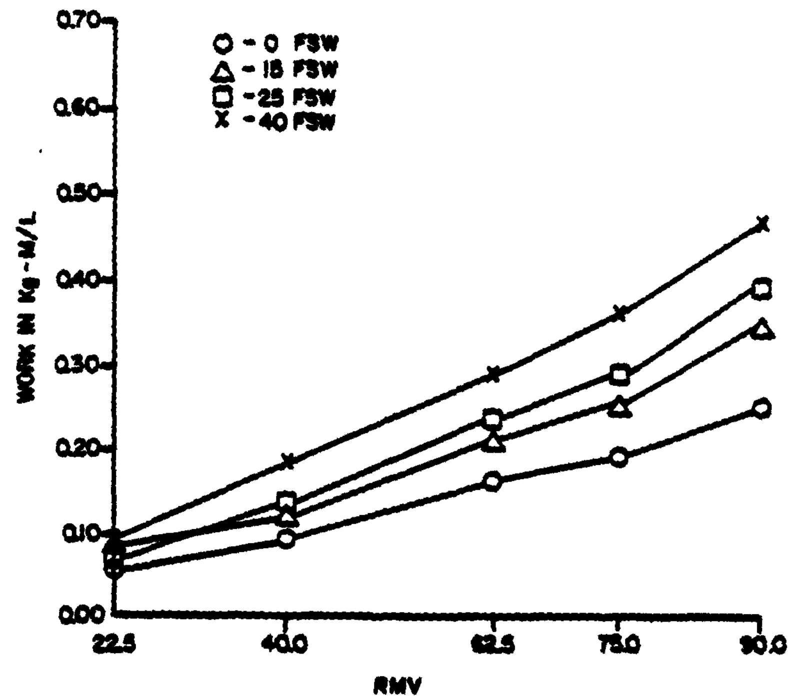


Figure 37. U.S. NAVY CLOSED-CIRCUIT SCUBA (EMERSON) BREATHING WORK vs. RMV

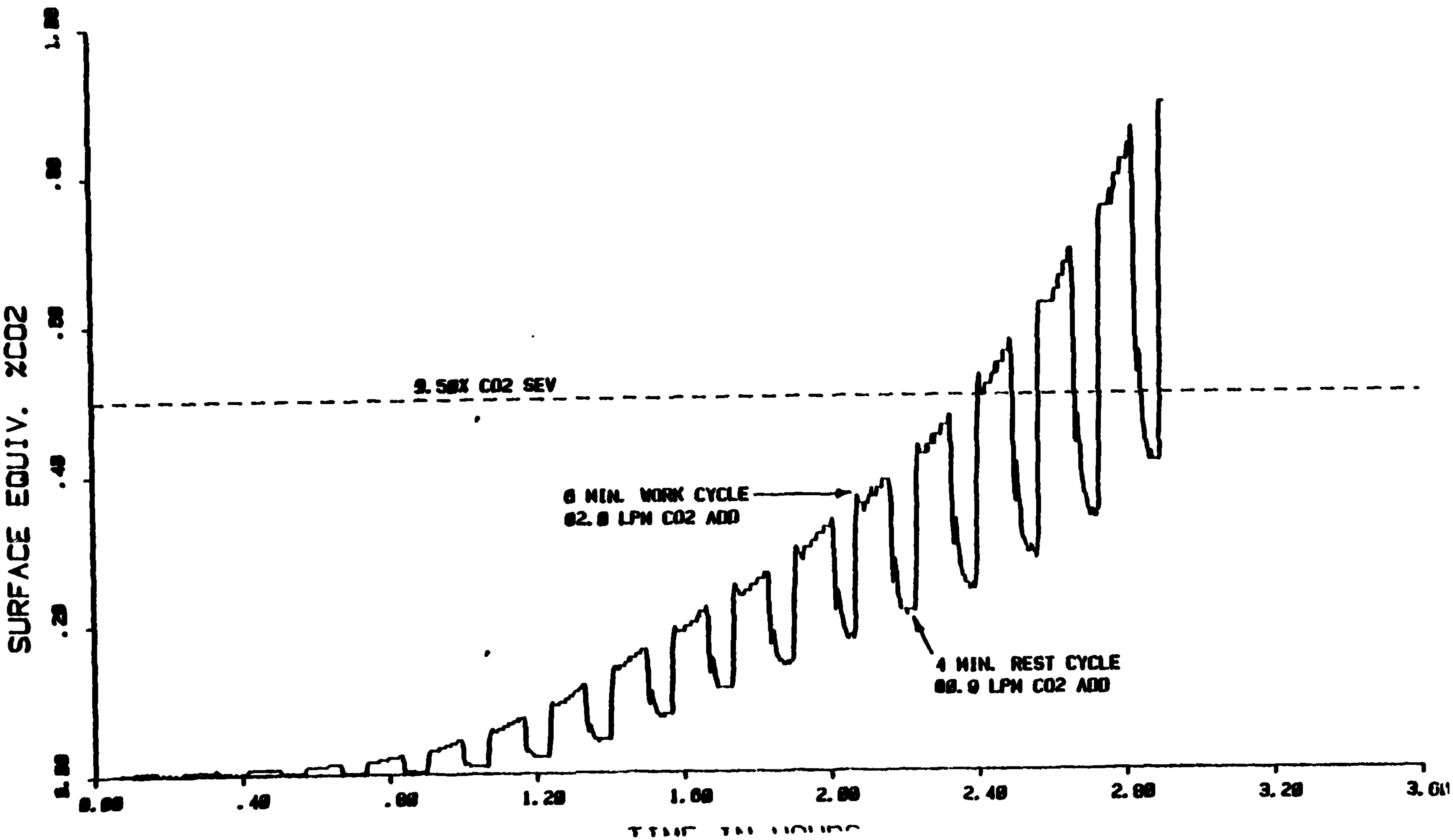
APPENDIX G

Canister Duration Data

Data for canister duration (% SEV vs time) is contained in this appendix for all six UBA's tested. Effluent out of the canister was monitored during all tests to a level of 0.88% SEV and test results are plotted to this point on each graph. Canister breakthrough is considered to occur at 0.50% SEV. Data is gathered beyond this point to more fully examine the operational limits of the equipment. Testing was terminated at 0.88% SEV due to inherent design limitations in the gas analysis equipment when used at very shallow depths.

KEY:

FIGURE 38
UBA: AGA OXYDIVE
WATER TEMP: 90'F
DEPTH: 25 FSW



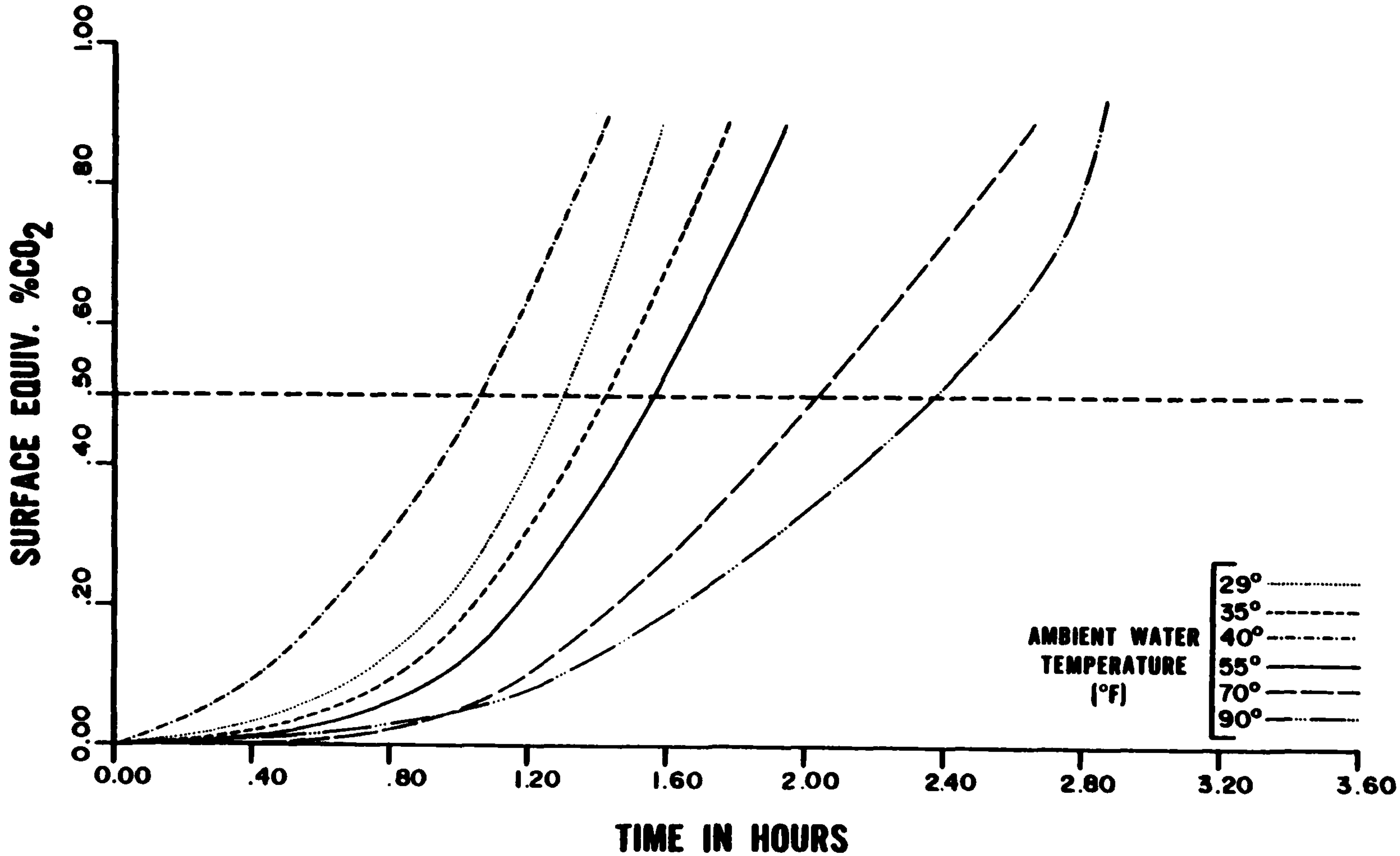


Figure 39. Canister Duration: % SEV CO_2 vs. Time
UBA: AGA OXYDIVE Depth: 25 FSW

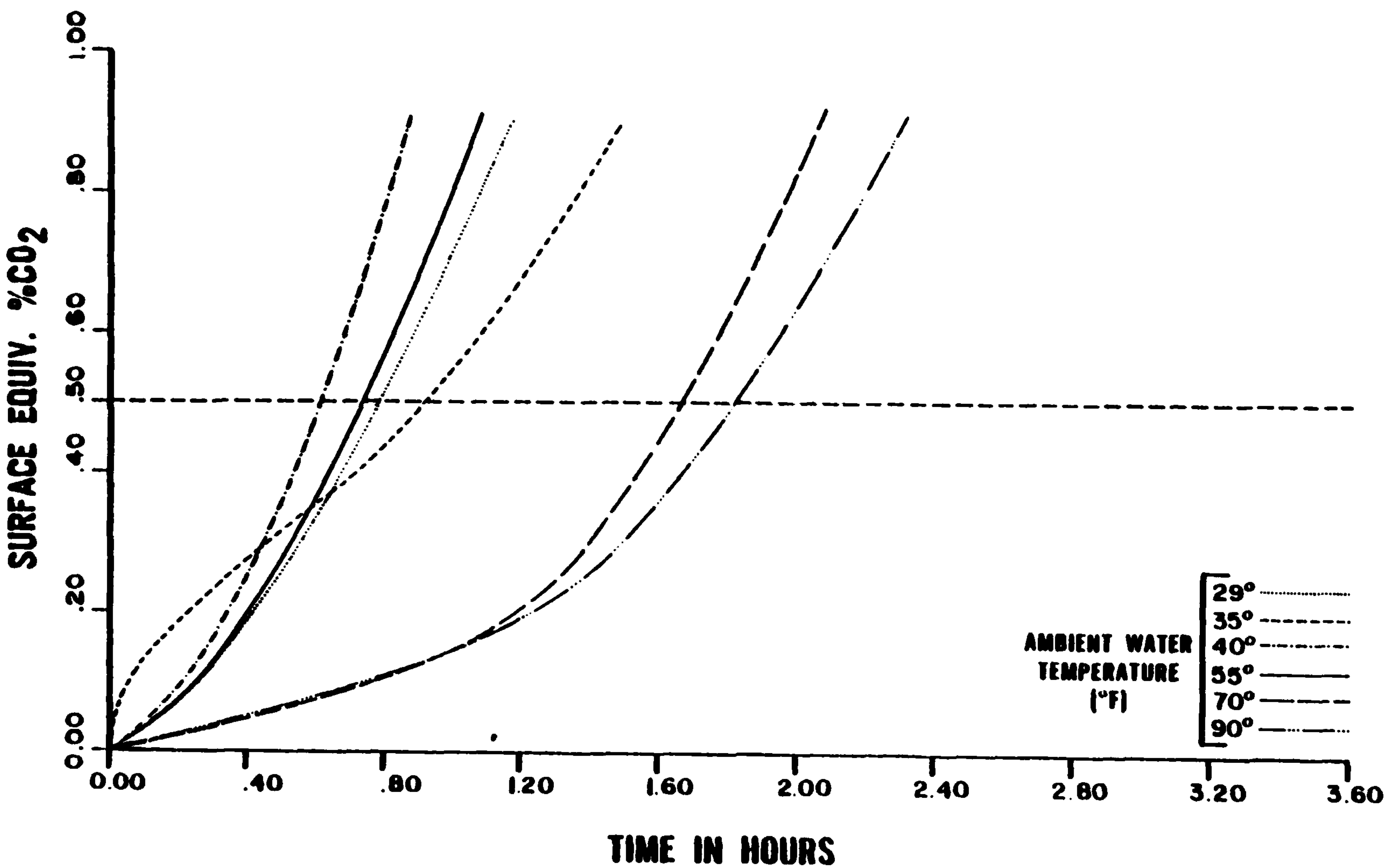


Figure 40. Canister Duration: % SEV CO_2 vs. Time
UBA: MOD BIOPAK 240 Depth: 25 FSW

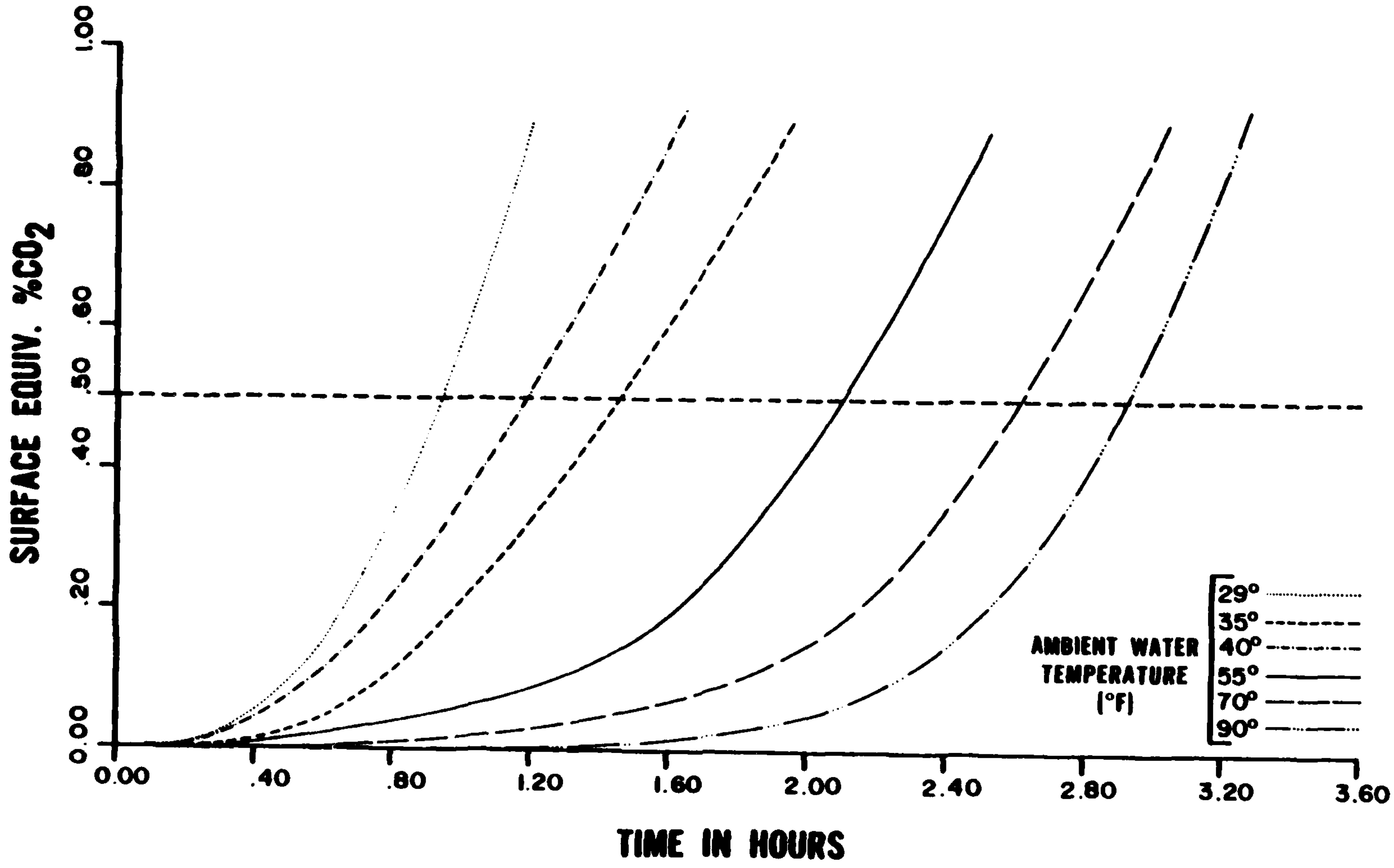


Figure 41. Canister Duration: % SEV CO_2 vs. Time
UBA: DRAEGER LAR V Depth: 25 FSW

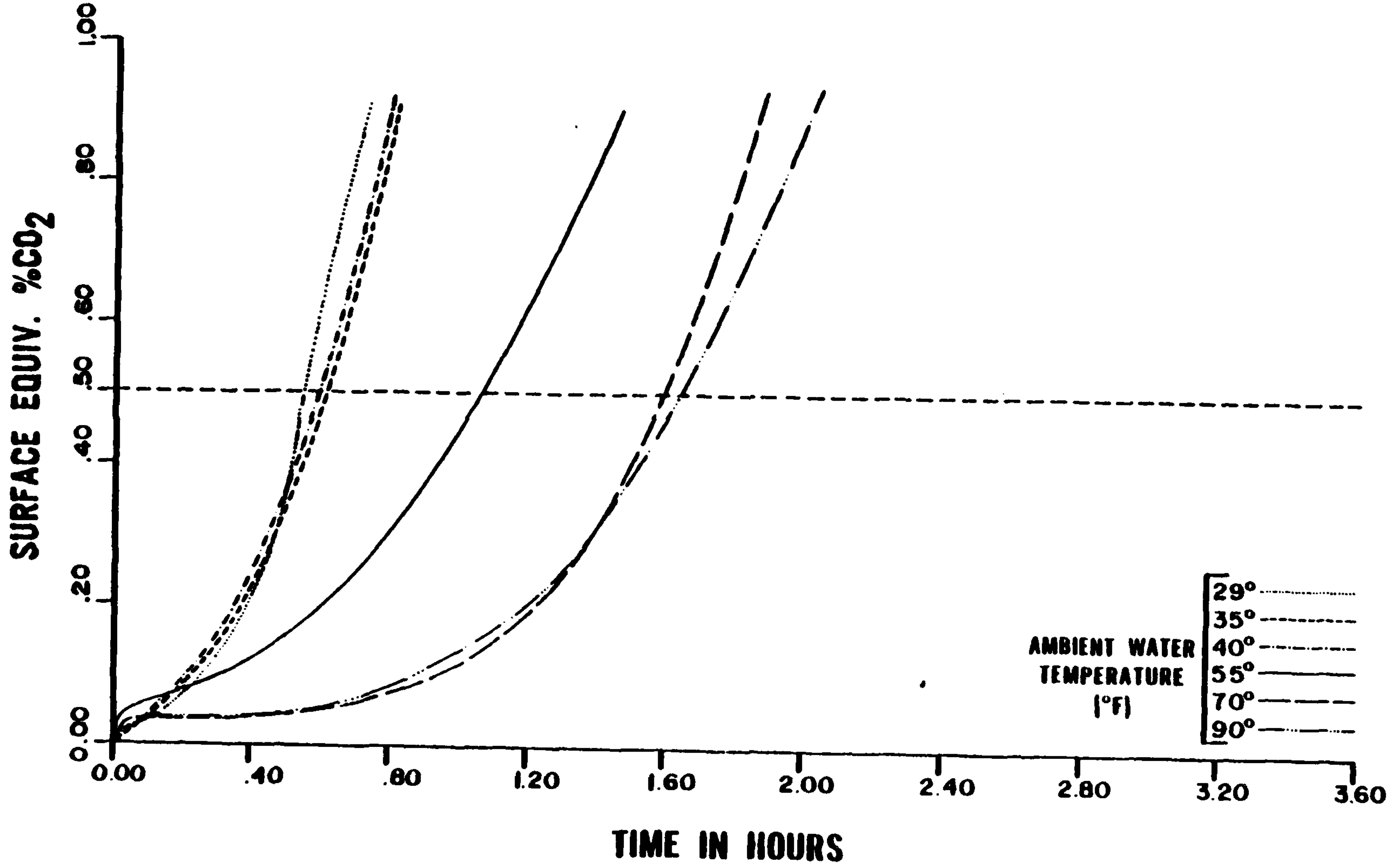


Figure 42. Canister Duration: % SEV CO_2 vs. Time
UBA: FENZY PO. 68 Depth: 25 FSW

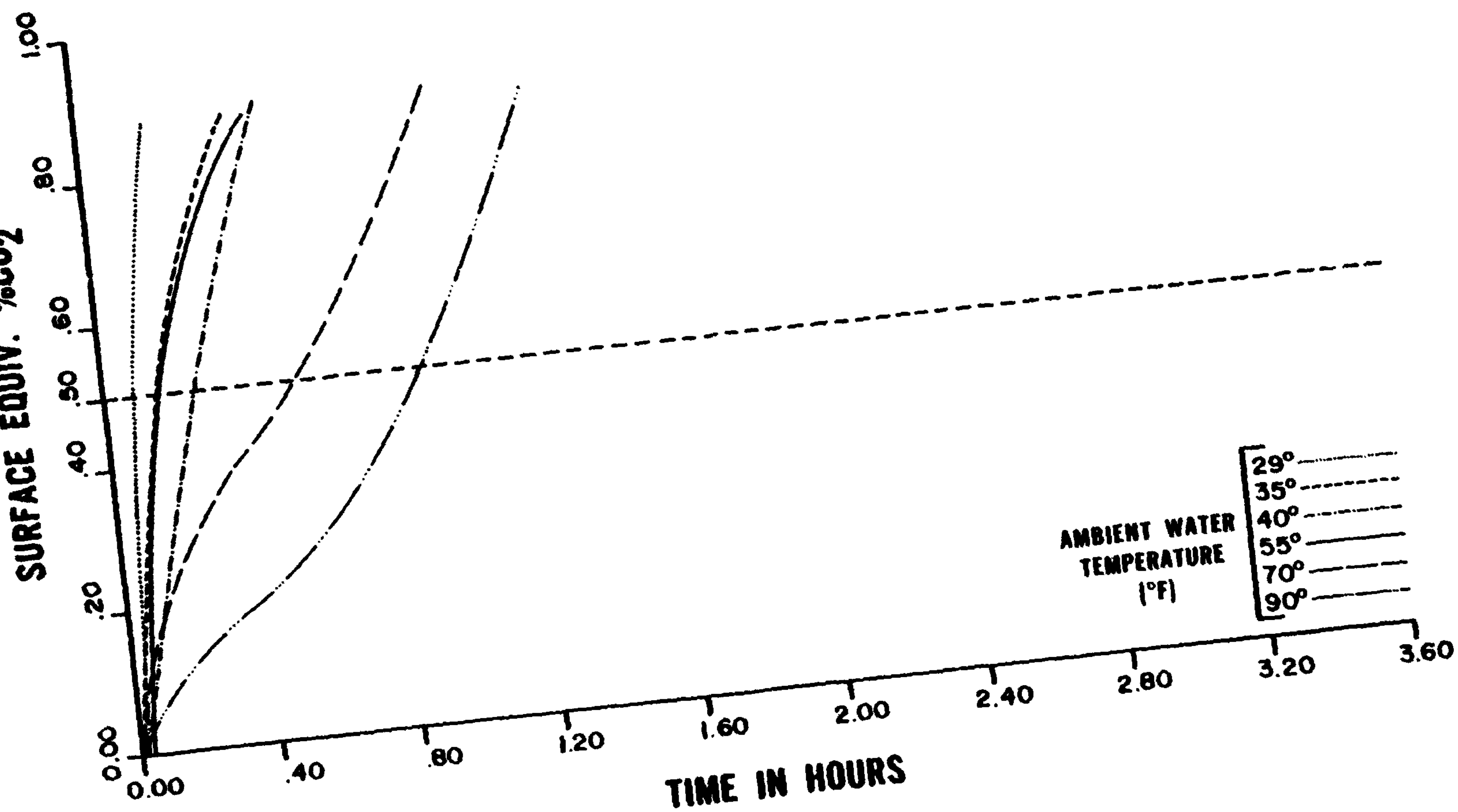


Figure 43. Canister Duration: % SEV CO_2 vs. Time.
UBA: SUBMARINE PRODUCTS OXYMAX 3 Depth: 25 FSW

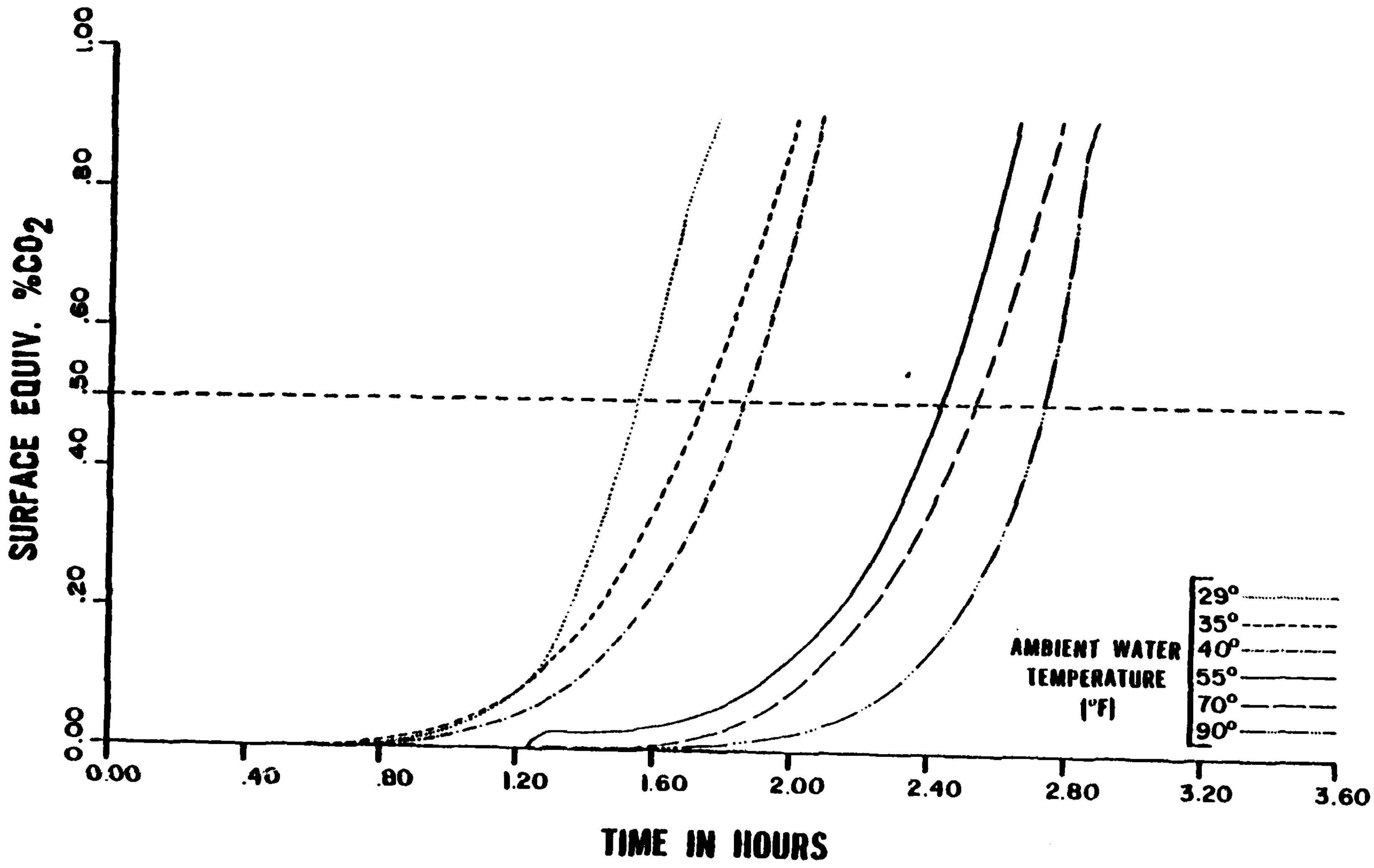


Figure 44. Canister Duration: % SEV CO_2 vs. Time.
UBA: U.S. Navy C/C O2 SCUBA (EMERSON) Depth: 25 FSW